

INFLUENCE OF COPPER AND ZINC POLLUTION ON FOREST VEGETATION

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SUMMARY

In the close vicinity of a foundry emitting Cu and Zn but virtually no SO₂, the concentrations of Cu and Zn in raw humus were 400 times and 80 times the respective concentrations found at remote sites (6-7 km). Four stages in the response of the ground-layer vegetation to the heavy-metal deposition were recognized:

- 1) The first signs of a decrease in the moss cover were observable where the Cu and Zn concentrations in the tissues reached values 3-5 times (Cu) and twice (Zn) the values found at remote sites. Mosses typical of mature coniferous forests (*Pleurozium schreberi*, *Hylocomium splendens*, *Ptilium crista-castrensis*, *Dicranum polysetum*) were the most sensitive species and were not found within 1 km of the foundry.
- 2) Lichens typical of mature dry forest communities (*Cladonia Cladina*, *C. uncialis*) were reduced in cover.
- 3) Pioneers typical of successional communities (*Cladonia Cladonia*) increased in cover; tolerant mosses retained their cover.
- 4) Even the *Cladonias* and the tolerant mosses, with the exception of *Pohlia nutans*, disappeared.

Epiphytic lichens suffered a reduction in cover. The thalli of *Hypogymnia physodes* were reduced in size.

Environmental variables, such as tree cover, percentage of rock outcrops and moisture of the soil surface, modified the response of mosses and lichens to pollution as revealed by environmental ordination (Reciprocal Averaging).

Field-layer species showed no response apart from a tendency for *Deschampsia flexuosa* to increase in cover towards the foundry.

Deterioration of the ground layer makes the polluted thin soil prone to erosion.

1 INTRODUCTION

It is widely recognized that the vegetation in the vicinity of factories emitting heavy metals is often impoverished (Pyatt 1970, Nash 1975, Westman 1975, Freedman & Hutchinson 1980). However, since these pollutants are often accompanied by SO_2 or other gaseous compounds, effects on the vegetation in areas where heavy metals constitute the sole pollutants have very rarely been investigated.

The sparsely inhabited surroundings of Gusum (1600 inhabitants, $58^\circ 15' \text{N}$, $16^\circ 33' \text{E}$, 150 km SW of Stockholm) lend themselves remarkably well to the study of this problem. Large amounts of heavy metals are emitted from an isolated brass foundry surrounded by coniferous woodland on thin podzol soils, a type of forest representative of much of Fennoscandia. The foundry in the centre of the village was founded in 1661. In 1968 a new foundry was built 1600 m from the old one which was closed down. Since the smokestacks of the disused foundry as well as those of the new foundry are low (< 30 m), the dispersal of the pollutants is geographically limited. This is one of the most heavily metal-polluted areas in Sweden. Copper and zinc in the form of oxides make up the bulk of the pollutants. Traces of lead, cadmium and nickel are also emitted, but essentially no SO_2 or other acidifying compounds. The damage to the vegetation can be studied without any severe interference from other anthropogenic factors, since there are no other local sources of air pollutants. For further details see Tyler (1976).

A reduction in decomposition processes and soil-enzymatic activities as well as changes in the populations of soil microfungi, higher fungi and earthworms have been demonstrated in the area (Tyler 1976, Rühling 1978, Bengtsson, Nordström & Rundgren 1983, Nordgren, Bååth & Söderström 1983). Further, metal uptake, photosynthesis and growth of mosses have been studied and damage to ground-layer mosses and epiphytic lichens has been documented (Folkeson 1979, 1981, Stjernquist 1981, Bengtson, Folkeson & Göransson 1982).

This study deals with the pollution effects on the vegetation (tree, field and ground layers as well as epiphytes). Special attention has been paid to the ground-layer mosses and lichens and the epiphytic lichens. Classification and environmental ordination (Reciprocal Averaging) of the data revealed that environmental variables considerably modify the influence of the heavy-metal pollution on the vegetation. The structure of the vegetation has thus been related to the steep heavy-metal gradient as well as to environmental variables.

The aims of the study were as follows:

- To investigate the structure of the vegetation in relation to the heavy-metal gradient and to environmental variables
- to identify species and groups of species that are sensitive to heavy-metal pollution and those that are tolerant
- to define the degree of pollution at which changes in the occurrence of some common species can first be registered.

2 MATERIALS AND METHODS

2.1 Distribution of quadrats

Within 7 km of the two foundries (the old disused foundry in the village and the new foundry outside the village) 180 quadrats were randomly distributed as shown in Table 1. The quadrats were denser towards the centre of the investigation area (Fig. 1). Each 25 x 25 m quadrat comprised a plot of fully grown coniferous forest on firm ground. Mires were avoided, but in many quadrats there were small patches of mire-like vegetation in moist depressions in rock outcrops. A certain degree of thinning of the stand was admitted.

2.2 Field work

The difference in height between the highest and lowest point within the 625 m² quadrat was estimated by eye to give a simple measure of the topography. The percentage of rock outcrops and

(in more than half the number of quadrats) the area (m^2) of steeply sloping bare rock were estimated by eye. Dryness of the soil surface and degree of exposure (degree of shelter, level of the quadrat in relation to the immediate surroundings, etc.) were assessed using simple four-point scales. Degree of thinning during recent years was estimated on a four-point scale based on the number of stumps and the amount of lying cut twigs.

Within the quadrats the *Pinus sylvestris* and *Picea abies* trees were counted and the total canopy density was estimated in per cent. Ground cover was estimated for the dwarf-shrub, herb, fern, grass, moss (Musci) and *Cladonia* species growing on rock, soil or raw humus as follows:

Degree of cover	Cover percentage, x
1	$x < 0.005$
4	$0.005 \leq x < 0.1$
5	$0.1 \leq x < 1$
6	$1 \leq x < 5$
7	$5 \leq x < 20$
8	$20 \leq x < 50$
9	$50 \leq x$

Ground cover for field-layer species was estimated after searching along c. eight parallel lines and for ground-layer species (i.e. mosses and lichens) along c. nine lines. Special attention was paid to rock crevices, steeply sloping bare rock and other parts of the quadrat where the ground-layer species were difficult to detect. Trunk bases, stumps and wind-blown trees were not investigated. *Spagnum* species were not kept separate, but their joint cover was estimated. Otherwise depressions in outcrops were disregarded.

Where possible, species were identified in the field, but many mosses had to be identified in the laboratory. *Cladonia uncialis* and species of subgen. *Cladina* were identified in the field. The total area covered by species of *Cladonia* subgen. *Cladonia* except *C. uncialis* was estimated in m^2 or dm^2 , and up to fifty small samples were brought to the laboratory to be identified to species.

The general occurrence of epiphytic lichen vegetation (as a whole; species not determined) on twigs and trunks of pine and of spruce was assessed on a four-point scale (see Table 10). For a more detailed analysis three pine trees (dbh > 20 cm; trunks not visibly inclined or bent) were selected: the one furthest to the south-west, the one furthest to the north-east and the one nearest to the centre of the quadrat. A ring was drawn round the trunk at breast height and a second ring 20 cm above this. The trunk segment was divided into quarters by vertical lines joining the rings on the NE, NW, SW and SE sides. Within each of the quarters of the segment the cover percentage of each fruticose and foliose lichen species was estimated. The size (and apparent condition) of the *Hypogymnia physodes* thalli was recorded on a three-point scale (Fig. 7). Mosses were not found within the trunk segments.

Where present in sufficient quantities, samples of *Dicranum polysetum*, *Hylocomium splendens*, *Hypnum cupressiforme*, *Pleurozium schreberi*, *Pohlia nutans*, *Cladonia rangiferina*, *Hypogymnia physodes*, *Pseudevernia furfuracea* and *Usnea* (mostly *filipendula*) were collected for metal analysis from at least three different patches. The sampling technique is described by Folkson (1979). No consideration was taken as to whether the specimens sampled from the ground grew under tree canopies or not. A knife was used to remove flakes of bark with *Hypogymnia physodes*, but apart from this no tools were used. Raw humus (0–2 cm) was sampled under *Cladonia rangiferina* and *Hylocomium splendens*. All the material was air-dried in paper bags.

Each day 2–3 quadrats were analysed. Areas investigated on consecutive days were usually far apart to avoid systematic error. The field work was done from 17 July to 17 October 1974 (zones 1–3) and from 15 July to 19 August 1975 (zones 4–7).

2.3 Laboratory work

The samples of mosses and lichens were identified. For each species (taxon) of *Cladonia* subgen. *Cladonia* (*C. uncialis* excluded) a cover value was calculated using the total cover of this species group and the proportion of the material collected

that each species constituted.

The nomenclature for phanerogams follows Lid (1974), for mosses Corley et al. (1981) and for lichens Hawksworth, James & Coppins (1980).

The fresh raw-humus material was crushed in a china mortar and dried at 105°C. A subsample (3–8 g dry wt) was ashed at c. 600°C to determine loss on ignition. To another 1 g, 20 ml of conc. $\text{HNO}_3 + \text{HClO}_4$ (10+1 v+v) was added. After digestion the samples were diluted with demineralized water. The concentrations of Ca (1% La^{3+} added), Cu and Zn were determined by AAS. The preparation and digestion of the plant material are described by Folkeson (1979). The concentrations of Na and K in the plant material were analysed by flame emission, Ca, Mg, Mn, Fe, Cu, Zn, Pb, Ni and Cd by AAS.

2.4 Statistical and numerical methods

Statistical analyses were carried out on the UNIVAC 1100 computer of the University of Lund, using different SPSS programs (Nie et al. 1975). Means and standard deviations of the environmental and chemical variables were calculated using the program CONDESCRIPTIVE. Relations between environmental, chemical and vegetational variables were tested by the rank-order correlation coefficient of Spearman, r_s , using the program NONPAR CORR.

Classification of vegetational structures was performed by an agglomerative method called relocated group clustering (van der Maarel 1979). This form of average linkage clustering (cf. Williams, Lambert & Lance 1966) is adopted in the table-rearrangement program TABORD (Persson 1977). The initial classification preceding the TABORD classification was made by a divisive program called DIVINF (Lance & Williams 1968). The field-layer vegetation and the ground-layer vegetation were classified separately. In the classification of the ground-layer vegetation all taxa recorded were included, but in the field-layer classification sixteen taxa (scattered seedling of the deciduous trees and shrubs) out of the 155 taxa were omitted.

The DIVINF program gave 16 and 18 initial clusters for the field-layer and ground-layer vegetation, respectively. Since the TABORD program is considered to be dependent to some extent on the initial clustering (van der Maarel 1979), initial clustering was also performed by randomly grouping the quadrats into twenty clusters, as well as grouping quadrats according to the distance zones. All three procedures gave the same final clusters, however.

By applying different limits to the threshold similarity values, below which a quadrat is not allowed to remain in a cluster but will be placed into a residual group because of outlier properties, the homogeneity of clusters can be stated according to ecological assumptions. The threshold limit was finally set to 0.40, whereby one and nineteen quadrats were placed in the residual group (0) at the classification of the field- and ground-layer vegetation, respectively. The fusion limit, regulating the number of final clusters, was raised in many steps and was finally set to 0.80. This high value indicates that only clusters with such a high similarity will be fused. The limit of constancy of species was set to 0.30.

Ordination of species as well as of environmental and chemical variables (see Fig. 2 for a list of the 52 variables) was made with the aid of Reciprocal Averaging, RA (Hill 1973) using a program called HILL (Persson 1978). RA is an eigenvector technique of indirect ordination related to standardized Principal Component Analysis (Gauch, Whittaker & Wentworth 1977). The advantage of RA is its ability to use a variable ordination to derive a quadrat ordination and vice versa. However, it may be sensitive to outlier quadrats.

Since the chemical variables contained many missing values, that data set was standardized to zero mean and unit variance using the SPSS program CONDESCRIPTIVE so that missing values were replaced by zero, i.e. the mean.

The effectiveness of an ordination can be judged to some extent from the measured eigenvalues of the axes outlined as well as from ecological interpretability. The first four axes of the RA ordination of the environmental and chemical variables accounted

for 0.58, 0.27, 0.22 and 0.19 of the variation, respectively, expressed in terms of measured eigenvalues. The corresponding values were 0.19, 0.16, 0.12 and 0.11 for the ground-layer vegetation and 0.25, 0.22, 0.18 and 0.17 for the field-layer vegetation. Reaching higher values and, in addition, revealing far more interpretable results, the environmental and chemical variables were chosen as a basis for the RA ordination. The graph of ordination axes 1 and 2 thus gives a pattern of the position of the quadrats in relation to the most important directions of variation in the environmental and chemical data.

On this graph of quadrats one can plot values of various vegetational variables, such as the cover of different species, as well as environmental and chemical variables. Such displays were obtained for a range of variables; some of the ecologically most interesting ones are presented in Fig. 2c-1. The graphs of the RA ordination axes 1 and 2 are based on data of 179 quadrats; the outlier quadrat no. 36, near the new foundry, was removed from the ordination since it had extreme values of all nine environmental variables and lacked values for all the chemical variables (mosses and lichens were not available for sampling).

3 RESULTS

3.1 Chemical and environmental gradients

The copper concentration in raw humus under *Cladonia rangiferina* showed a steep gradient in the area rising from 20–25 $\mu\text{g}\cdot\text{g}^{-1}$ 6–7 km from the nearest of the two foundries to 8400 $\mu\text{g}\cdot\text{g}^{-1}$ at the sampling site next to the new foundry (Fig. 1). Moss studies (Rühling & Skärby 1979, Bengtson, Folkeson & Göransson 1982) showed that the regional background concentrations were not found within 8 or even 12 km of the foundries. Since there were no distinctly prevailing winds, the isarithms were roughly circular. They were centered on the location of the new foundry and only slightly extended around the old one.

Copper and zinc were the dominant pollutants and their concentrations in raw humus in the area were closely correlated with each other ($r_s=0.98$; Fig. 1). The zinc gradient was less steep,

however, the level increasing from 80–100 $\mu\text{g}\cdot\text{g}^{-1}$ at 6–7 km to 6300 $\mu\text{g}\cdot\text{g}^{-1}$ close to the new foundry. The metal gradients gave rise to high correlation coefficients for the relations of copper and zinc concentrations in raw humus with proximity to the new foundry (Table 2).

The strong copper-zinc gradient was manifested in the RA ordination of environmental and chemical data by high loadings at both ends of axis 1 and at the positive end of axis 2 (filled circles in Fig. 2a). The copper and zinc concentrations were highly intercorrelated in all the materials. There were relatively few missing values (13–31% of the quadrats) for the copper and zinc concentrations in raw humus under *Cladonia rangiferina* and under *Hylocomium splendens* and in tissues of *C. rangiferina* and *Hypogymnia physodes*. These eight variables had the highest positive loadings on the first axis (filled circles numbered 10–17). There were many more missing values (43–64%) in the variables that had the most negative loadings on the first axis. These variables (filled circles numbered 18–31) included copper and zinc concentrations in seven other plant materials. An intermediate number of missing values (32%) was found for the copper and zinc concentrations in *Pseudevernia furfuracea* at the positive end of the second axis. The other metals (lead, nickel, cadmium, iron, manganese, magnesium and calcium) had intermediate loadings on the axes. Thus the first as well as the second axis of the RA ordination primarily displayed the copper-zinc gradient.

Since the first three RA axes turned out to be to some extent dependent on each other, which is common in RA ordinations on vegetation data as well (Gauch, Whittaker & Wentworth 1977), some of the variation concealed by the strong copper-zinc gradient was revealed by a set of the next three RA axes. Therefore a display of axis 1 and axis 4 explained more independent, though slightly smaller, parts of the total variance in the data, expressed in terms of eigenvalues. The variables number of spruce trees and canopy density were at the positive end of the fourth axis (filled squares in Fig. 2b) and exposure, dryness of the soil surface and rock-outcrop percentage were at the negative end. These five environmental variables thus constitute important factors for the structure of the vegetation.

The structure of the vegetation will be discussed in relation both to the environmental factors assessed and to the strong chemical gradient, often represented by the copper or the Cu+Zn concentration in raw humus under *Cladonia rangiferina*, since these were the chemical variables where the highest number of quadrats were included. The concentrations in raw humus give an integrated picture of the metal load over many years (Fig. 1). The display of the copper concentration in raw humus shows a gradient from left to right in the graph of RA ordination axes 1 and 2 (Fig. 2c). However, the influence of the environmental factors makes the quadrats spread out also along axis 2.

In addition to copper and zinc, some other metals show gradients, though weaker, in the area as well. The emission of small quantities of lead and nickel have given rise to gradients in these concentrations in *Cladonia rangiferina* (Table 2). The levels of some other metals were also higher near the foundries. The epiphytic lichen *Hypogymnia physodes* gave the same picture for copper and zinc as did *Cladonia rangiferina*, but for the other metals the two species often differed, *H. physodes* showing lower correlation coefficients in many cases. Some metals tended to increase with the distance. To sum up, the metal load in the Gusum area was dominated by copper and zinc, but for lead, nickel, iron and a few other metals somewhat elevated concentrations could be measured in lichens and mosses within c. 2 km of the foundries.

3.2 Ground-layer vegetation

3.2.1 Structure

In the 180 quadrats investigated, fifty-seven moss (Musci) and twenty-five *Cladonia* taxa were recorded. The nine clusters generated by the TABORD classification were highly discrete (fusion limit 0.80) and fairly homogeneous; the threshold limit (0.40) moved nineteen outlier quadrats to the residual group 0 (Table 3). By applying χ^2 tests the significant belonging of a species to a cluster was evaluated. Like the fusion limit this test also manifested the separation of clusters. The nine clusters and the residual group were thus treated as ten groups

of equal importance. All Musci and Cladonia taxa were included in the classification, but thirty-two taxa with a frequency of less than 25% in any of the ten groups were omitted from Table 3 to save space.

Many taxa decrease in cover from group 1 to group 9 (Table 3). This is especially true of the quantitatively important taxa. Of these, *Ptilium crista-castrensis*, *Aulacomnium palustre* and *Dicranum polysetum* had their high cover values confined to quadrats of groups 1 and 2, *Hylocomnium splendens*, *Pleurozium schreberi*, *Hypnum cupressiforme* and *Dicranum scoparium* to groups 1-4, *Cladonia rangiferina* and *C. arbuscula* to groups 1, 2, 4 and 5, *Sphagnum* spp. to groups 2 and 5 and *Cladonia stellaris*, *C. uncialis*, *Polytrichum commune* and *C. gracilis* to groups 2, 4 and 5. The quadrats in groups 6, 7, 8, 9 and 0 had only scattered occurrences of the species mentioned except for *Hypnum cupressiforme* and *Polytrichum commune*. The TABORD program thus placed many quadrats rich in species, often with high cover values, into group 2. The quadrats of group 9, on the other hand, contained only thirteen species, of which only *Pohlia nutans* had a cover value exceeding 0.1% of the ground.

The quadrats that were more than 4 km from the foundries all belonged to groups 1 or 2 (Fig. 3). The quadrats in group 3 were found at a distance of 1-4 km. The groups 4 and 5 were mainly represented in zone 2 (1-2 km) or in the fairly sheltered SE part of the innermost zone. The quadrats of groups 6-8 were 600-1900 m from the nearest foundry. Apart from one quadrat close to the new foundry the quadrats in group 9 were close to each other in the near vicinity of the old foundry. Finally, all but one of the 19 quadrats of group 0 were situated very close to the new foundry. Quadrats belonging to groups with low numbers were thus far from the foundries and quadrats with higher group numbers (0 included) were closer to the foundries.

The mean concentrations of copper and zinc in raw humus gradually increased from classification groups 1 to 7 (Fig. 4). The heavy-metal levels in samples from quadrats of groups 9 and 0 were far higher than those of the other groups. The same copper and zinc gradient could be recognized in the lichen *Cladonia*

rangiferina itself (Table 4). The concentrations of lead, nickel and iron were raised in samples from groups 6, 7, 8, 9 and 0, while the manganese and calcium concentrations were raised in samples from groups 0 and 9 only. The other metals analysed showed little variation between quadrats; the concentrations usually varied within the following ranges:

Na 50-120, K 1000-1800, Mg 180-250 and Cd $0.2-0.6 \mu\text{g}(\text{g dry wt})^{-1}$.

All quadrats belonging to the classification groups 1, 2 or 3 were on the lower left of the graph of the RA ordination axes 1 and 2 (Fig. 2d). These quadrats also had the lowest heavy-metal load (Fig. 2c). At the other extreme all but two quadrats of groups 8, 9 and 0 had copper levels in the raw humus exceeding $300 \mu\text{g}\cdot\text{g}^{-1}$. Most of the quadrats of groups 4-7 were in the middle part of the copper gradient.

Compared with groups 1-4, the number of moss taxa was much lower in quadrats of groups 5-8 and still lower in quadrats of groups 9 and 0, the groups most loaded with heavy metals (Table 5). The mean number of *Cladonia* taxa was highest in groups 2, 4 and 5 and lowest in groups 9 and 0. The number of moss taxa per quadrat was highly correlated with distance from the foundries and (negatively) with copper load of the raw humus. The number of *Cladonia* taxa showed lower correlation coefficients for these relations (Tables 6 and 7).

Superimposed on this distinct chemical gradient and independent of it, considerable variation in biotic and environmental features between the groups was found. Quadrats in groups 1, 3, 4, 6, 7 and 0 were mainly dominated by spruce and the canopy density and rock-outcrop percentage varied greatly among the groups. Quadrats in groups 2, 5, 8 and 9 were mainly dominated by pine. The quadrats of these groups were more equal according to fairly low canopy densities and high rock-outcrop percentages (Table 5). Other environmental variables influencing the ground-layer vegetation are topography, the area of steeply sloping bare rock, degree of exposure, dryness of the soil surface and the cover and composition of the field layer. The degree of thinning, however, rarely had any significant influence on the ground-layer vegetation. The most important of the variables

mentioned are included in Tables 5-8 and Fig. 2a and b.

To sum up, the quadrat groups generated by the classification program varied greatly in species diversity and cover of the common ground-layer species. The location of quadrats of the different groups showed a clear geographical pattern in relation to distance from the foundries. The steep gradient in the heavy-metal load in the area was expressed in a distinct chemical differentiation between the quadrat groups. Environmental variables considerably modified the strong influence of the heavy-metal pollution on the structure of the ground-layer vegetation.

3.2.2 Distribution of individual species

3.2.2.1 Mosses

Most of the moss species each covered less than 5% of the ground. In the Gusum area, cover values of 20% or more were attained by five species only, *Pleurozium schreberi*, *Hylocomium splendens*, *Dicranum polysetum*, *Ptilium crista-castrensis* and *Pohlia nutans* (Table 3).

At unpolluted sites the four most abundant species, *Pleurozium schreberi*, *Hylocomium splendens*, *Dicranum polysetum* and *D. scoparium*, together covered 20-40% of the ground, sometimes 50 or even 75%. These are four of the moss species that are most sensitive to copper and zinc, however. The cover values began to decrease where the copper and zinc concentrations in the moss tissue had risen to 3-5 and 2 times the respective value found in the remote quadrats, $10-18 \mu\text{g}\cdot\text{g}^{-1}$ of Cu and $75-120$ of Zn (Table 9). There was a steady reduction in cover with increasing metal load. These mosses could usually survive with a maximum load of about $80-110 \mu\text{g}\cdot\text{g}^{-1}$ of Cu and $300-400 \mu\text{g}\cdot\text{g}^{-1}$ of Zn at the most.

Pleurozium schreberi

Pleurozium schreberi was the only moss species that attained the cover value of 9 (>50% coverage), except for *Hylocomium*

splendens in a single quadrat. In 60% of the quadrats in the three most remote zones (distance >4 km), *P. schreberi* covered more than 20% of the ground (Fig. 5). The cover values gradually decreased with increasing metal load and decreasing distance from the foundries, however. Cover values of 8 and 9 were not found where the copper level in the moss tissue exceeded $32 \mu\text{g}\cdot\text{g}^{-1}$, and the zinc level 180. Nowhere in the innermost zone did the cover exceed 0.1%. Here live moss was only found in sheltered habitats such as rock crevices or behind large stones. In the vicinity of the new foundry blackened and non-decomposed remnants of dead *P. schreberi* tissue were found everywhere, often in considerable amounts and in some places covered by litter from conifers. Near the old foundry not even dead remains were found.

The distinct cover gradient was reflected in the high correlation coefficients for the relation of cover to distance from the foundries or Cu+Zn load of the raw humus (Table 6). Somewhat lower though still highly significant correlations were obtained for the Cu+Zn content in the moss tissue reflecting the loss of a great number of highly polluted quadrats where there was not enough moss tissue for sampling.

The mean cover was highest in the quadrats of the classification group 1. Many of these quadrats had a dense tree cover and a very low percentage of rock outcrops (Tables 3 and 5). However, high cover values were also typical of group 2 where open pine-forest quadrats rich in rock outcrops prevailed. In reasonably non-polluted quadrats the cover increased significantly with tree-canopy density and decreased with the percentage of rock outcrops (Table 6).

The display of the cover of *Pleurozium schreberi* on the graph of the RA-ordination axes 1 and 2 shows the distinct connection between cover and heavy-metal load (Fig. 2c and 2e). One third of the quadrats were devoid of live *P. schreberi*. These are all in the right half of the ordination diagram. The quadrats where only dead moss tissue was found are mainly restricted to the area of quadrats where the copper level in the raw humus exceeds $300 \mu\text{g}\cdot\text{g}^{-1}$.

Hylocomium splendens

Hylocomium splendens was the second most abundant moss. In half the number of quadrats more than 4 km from the foundries this feather moss covered 5% or more of the ground. The reduction in cover was similar to that for *Pleurozium schreberi*. *Hylocomium splendens* was able to survive with $130 \mu\text{g}\cdot\text{g}^{-1}$ of Cu and $360 \mu\text{g}\cdot\text{g}^{-1}$ of Zn in its tissue at most (Table 9). Zone 1 was almost devoid of the species but as with *P. schreberi*, *H. splendens* was frequently found dead within 1800 m of the new foundry.

The relation of cover to distance and metal load was slightly weaker than in the case of *Pleurozium schreberi*, possibly owing to the fact that the cover of *H. splendens* was usually somewhat lower than that for *P. schreberi* in non-polluted quadrats (Table 6). The seventy-four samples where metal analyses could be performed represent scarcely or slightly polluted quadrats, which explains the low r_s for the relation between the cover and the metal level in the moss tissue.

The cover diminishes from group 1 to group 6; the quadrats of the other groups were devoid of the species (Table 3). The RA-ordination display of *H. splendens* closely resembles that for *Pleurozium schreberi*. These two feather mosses were also alike in their relationships to rock-outcrop percentage and canopy density (Table 6).

Ptilium crista-castrensis

This feather moss was common only in fairly remote areas. It was rarely found in zone 2, never in zone 1. It had high cover values in almost every quadrat of group 1. Though not uncommon in group 2 either, it was almost totally lacking in the quadrats of the other groups. This bryophyte was decidedly restricted to unpolluted, dark and moist habitats with few rock outcrops (Fig. 2f, Tables 5 and 6).

Dicranum polysetum

All the quadrats where *Dicranum polysetum* reached its highest cover value (8) were found in the outermost zone, 6-7 km. There was a continuous reduction in cover as the foundries were approached. Likewise, the frequency decreased from 100% in zones 5-7 to 45% in zone 2 and zero in zone 1. Like the three feather mosses mentioned above, *D. polysetum* showed a close relation between cover and the heavy-metal gradient (Table 6). The relation to rock-outcrop percentage and canopy density was less pronounced, however. Though it otherwise resembled *Pleurozium schreberi* and *Hylocomium splendens* in cover behaviour, *D. polysetum* showed a marked decline in cover already in the quadrats of group 3 (Table 3). The species was completely lacking in quadrats of groups 6 and higher, and the area where the species was lacking extends further left in the ordination graph than for *Pleurozium schreberi* and *Hylocomium splendens* (Fig. 2g).

Dicranum scoparium

This species reacted in much the same way as *Dicranum polysetum*, but scattered finds were also recorded from the innermost zone. In the slightly polluted quadrats, its cover was somewhat lower than for *D. polysetum*, but in quadrats with moderately high heavy-metal levels, the opposite seemed to be true (Table 3) so that r_s values were slightly lower for *D. scoparium* than for *D. polysetum* (Table 6). *Dicranum scoparium* was more associated to quadrats with a low rock-outcrop percentage and a high canopy density than was *D. polysetum*.

Aulacomnium palustre

Like *Ptilium crista-castrensis*, *Aulacomnium palustre* was almost entirely confined to quadrats of groups 1 and 2 (Table 3). It was seldom found in zone 2, never in zone 1. It is undoubtedly a metal-sensitive species but shows no obvious preferences as to rock outcrops or canopy density (Table 6).

Hypnum cupressiforme

Although present also in zone 1, this moss was reduced in cover where the copper concentration in its tissue exceeded c. $60 \mu\text{g}\cdot\text{g}^{-1}$ (Table 9). At places, it was present also in quadrats with high heavy-metal load, and the r_s values were comparatively low (Table 6). The cover seemed to be higher in dark habitats with a marked topography.

Polytrichum commune

This species seemed to be fairly unaffected by the heavy-metal load, but it evidently preferred sparsely wooded habitats abounding in rock outcrops (Table 6).

Pohlia nutans

Pohlia nutans was the most frequently found species, being present in 95% of the quadrats (Table 3). Rather low cover values were encountered in quadrats of group 0, but otherwise cover varied only slightly from group to group. The cover showed no significant relation to distance from the foundries or heavy-metal load either in raw humus (Table 6, Fig. 2h) or in the tissue. However, it tended to prefer open hilly habitats with abundant outcrops (Table 6).

Other mosses

Only eight moss taxa were found in all the quadrat groups. *Andreaea rupestris*, *Bartramia pomiformis*, *Hedwigia ciliata*, *Paraleucobryum longifolium*, *Polytrichum juniperinum* and *Racomitrium heterostichum* were all largely restricted to rocky habitats with a low tree-canopy density (Tables 3, 5 and 6). On the contrary, *Brachythecium* spp., *Plagiomnium affine* and *Rhytidiadelphus triquetrus* were typical of densely wooded moister habitats with a low rock-outcrop percentage.

Though seldom reaching high cover values, *Andreaea rupestris*, *Bartramia pomiformis*, *Brachythecium* spp., *Cynodontium strumiferum*, *Dicranum montanum*, *Isopterygium elegans*, *Plagiothecium*

curvifolium, *P. denticulatum*, *P. laetum* and *Racomitrium heterostichum* were found also in some heavily polluted quadrats.

It should be borne in mind that the presence and coverage of the different species form the basis for the classification of quadrats into groups. The groups formed by TABORD are merely artificial units, but placed in relation to their environmental and chemical characteristics the classification groups help explain the structure of the vegetation and the underlying differentiating factors.

3.2.2.2 *Cladonia* lichens

A total of twenty-five *Cladonia* taxa were recorded from the quadrats. Groups 2, 4 and 5 are characterized by a high number of species. In addition group 2 shows high cover values of many species. Rather low canopy densities and high out-crop percentages were found in quadrats of these three groups (Tables 3 and 5).

Cladonia Cladina

The lichens *Cladonia arbuscula*, *C. rangiferina* and *C. stellaris* occurred in abundance in most quadrats of group 2 but they were low in cover or frequency in the quadrats of 3, 6, 7, 8, 9 and 0 (Table 3). The dominant reindeer lichens *C. rangiferina* and *C. arbuscula* were found in every quadrat in groups 2, 4 and 5, often in great quantities. Fairly high coverages were also typical of group 1. Like the feather mosses, *C. rangiferina* (and *C. arbuscula*) was absent from the quadrats with high loads of heavy metals (Fig. 2i). These lichens, too, were often found dead and blackened in the most polluted quadrats in the close vicinity of the new foundry. However, they were also lacking in some unpolluted quadrats without bare rock; by contrast the highest cover values, 7 and 8, were often associated with rock-outcrop percentages of 70 or more (Fig. 2j).

Though characterized by a statistically significant negative correlation to the heavy-metal load, these three lichens showed a considerably stronger relation to rock-outcrop percentage

(positive) and canopy density (negative) (Table 7).

Cladonia Cladonia

Cladonia chlorophaea agg. appeared in large amounts in quadrats of groups 2-8, *C. uncialis* and *C. gracilis* in groups 2, 4 and 5, *C. fimbriata* and *C. furcata* in groups 4 and 6, *C. squamosa* in group 2 and *C. cornuta* in group 4 (Table 3). *Cladonia chlorophaea* agg., *C. coniocraea* et *ochrochlora*, *C. squamosa*, *C. gracilis* and *C. cornuta* retained a fairly high frequency in all groups except 9 and sometimes some additional group.

The pattern of the cover *C. chlorophaea* agg. in the RA-ordination graph differs from that for all hitherto mentioned taxa; the highest cover value (6) was found in the middle of the copper gradient, where the copper concentration in raw humus was c. $300 \mu\text{g}\cdot\text{g}^{-1}$ (Fig. 2c and 2k). Quadrats lacking the taxon were scattered all over the RA graph. For *C. coniocraea* et *ochrochlora*, *C. cornuta*, *C. fimbriata*, *C. furcata* and *C. gracilis* as well there is an indication of a slight increase in cover with increasing copper concentration up to c. $700 \mu\text{g}\cdot\text{g}^{-1}$ in raw humus (Table 7). It is worth to notice that in a few of the most polluted quadrats, high coverages were registered for some taxa of *Cladonia Cladonia* (*C. chlorophaea* agg., *C. fimbriata*, *C. gracilis*, *C. cornuta*, *C. carneola*, *C. cenotea*, *C. bacillaris* et *floerkeana* and *C. subulata*). On the contrary, *C. uncialis* was lacking in the most polluted quadrats (Table 3). The cover of *C. chlorophaea* agg., *C. cornuta*, *C. gracilis* and *C. uncialis* reveals a positive correlation with rock-outcrop percentage and topography, and a negative correlation with the canopy density (Table 7).

The number of *Cladonia* taxa increased with distance from the foundries and thus decreased with the degree of pollution. The r_s values are lower than for mosses, however (Table 6). In contrast to the mosses the species diversity of *Cladonia* lichens was highly influenced by rock-outcrop percentage and canopy density, less so by topography.

3.3 Field-layer vegetation

A total of 155 field-layer taxa were recorded. *Vaccinium myrtillus* and *V. vitis-idaea* were present in every quadrat except one (quadrat 115 next to the old foundry) which was devoid of field-layer vegetation.

Group 1, comprising 106 quadrats, was separated from group 2, comprising 73 quadrats, mainly due to the fact that the following species were highly significantly ($p < 0.01$) present in group 1 and absent ($p < 0.01$) from group 2: *Agrostis tenuis*, *Anemone nemorosa*, *Anthoxanthum odoratum*, *Calamagrostis arundinacea*, *Campanula persicifolia*, *Dryopteris filix-mas*, *Festuca ovina*, *Fragaria vesca*, *Hieracium Sylvatica*, *H. Vulgata*, *Lathyrus montanus*, *Luzula pilosa*, *Maianthemum bifolium*, *Melampyrum pratense*, *Melica nutans*, *Oxalis acetosella*, *Potentilla erecta*, *Pteridium aquilinum*, *Solidago virgaurea*, *Trientalis europaea* and *Viola riviniana*. On the other hand, *Calluna vulgaris*, *Pinus sylvestris* (seedlings) and *Vaccinium uliginosum* were significantly ($p < 0.01$) present in group 2. The residual group consisted of the bare quadrat 115.

Several set-ups of options all resulted in groups which had no evident connection with the heavy-metal gradient in the area. Obviously, the field-layer vegetation was more dependent on soil characteristics and other environmental factors than on the pollution. On the other hand the field-layer, directly or indirectly, influenced the structure of the ground-layer vegetation (Table 5).

There was no obvious relation between the heavy-metal gradient and the distribution of individual field-layer species. With the exception of the denuded quadrat 115, the most polluted quadrats close to the foundries showed no signs of impoverishment of the field-layer vegetation. On the contrary, *Deschampsia flexuosa* had a tendency to increase slightly in cover with decrease in distance from the foundries. Cover values exceeding 5% of the ground were recorded from 41% of the quadrats belonging to the ground-layer classification groups 1-3, from 58% of the quadrats of groups 4-7 and from 65% of the quadrats

of groups 8, 9 or 0 which were the most heavily polluted (Fig. 6).

3.4 Epiphytic lichen vegetation

3.4.1 General occurrence on trunks and twigs

The general occurrence of epiphytic lichen vegetation on trunks and twigs of *Pinus sylvestris* and *Picea abies* was clearly reduced within a few kilometres of the foundries. Within a radius of 1 km, the epiphytes on spruce twigs were lacking or nearly so in 60% of the quadrats, 0% of the quadrats more than 2 km distant. In the periphery of the area, concentrations in epiphytic *Hypogymnia physodes* were 11-15 $\mu\text{g}\cdot\text{g}^{-1}$ for Cu and 25-140 $\mu\text{g}\cdot\text{g}^{-1}$ for Zn (Table 9). Lichen material could be collected in all but the most heavily polluted quadrats. The copper and zinc concentrations were found to increase steadily until maxima of c. 1000 $\mu\text{g}\cdot\text{g}^{-1}$ of Cu and 2000 $\mu\text{g}\cdot\text{g}^{-1}$ of Zn were reached. The first effects on the occurrence of epiphytes could be registered when the metal levels had increased 5-7-fold for copper and 3-5-fold for zinc (Table 9).

The impoverishment of the epiphytic vegetation in the vicinity of the foundries gave rise to highly significant though numerically rather low correlation coefficients for the relation between lichen occurrence and distance or heavy-metal content in either raw humus or epiphytic *Hypogymnia physodes* (Table 10). Of the quadrats more than 2 km away those rich in rock outcrops tended to have a more abundant lichen vegetation but canopy density, degree of thinning and topography had mostly very little influence on the epiphytes.

The RA-ordination graph of the occurrence of lichens on spruce twigs reveals a close agreement between the disappearance of lichens and the increase in heavy-metal pollution (Fig. 2c and 2 1).

3.4.2 Cover in quarters of pine-trunk segments

The epiphytic lichen vegetation in the segments of pine trunks was highly dominated by *Hypogymnia physodes*; the other taxa had

only low cover values and varied greatly in frequency in the different classification groups (Table 11; groups still refer to the classification of the ground-layer vegetation). The quadrats of group 9 had low frequencies of all taxa except for *Parmeliopsis ambigua*, and *Bryoria* spp. and *Usnea* spp. were only occasionally registered there. Many species were frequent in quadrats of groups 2 and 5 which constituted many sparsely wooded quadrats rich in outcrops.

The special study devoted to *Hypogymnia physodes* revealed that the species was present in 93% or more of the segment quarters of the trunks of pines in all groups except for group 9 (Table 11). The mean cover was highest in quadrats of group 3 and lowest in group 9; groups 7, 8 and 0 also tended to have somewhat lower cover values than the other groups, at least in the northern quarter of the trunk segments (Fig. 7).

The thalli of *Hypogymnia physodes* within the trunk segments were estimated as large or of normal size in most of the quadrats in groups 1-6, at least as far as northern and eastern quarters of the stem segments are concerned. The size score implying tiny and stunted thalli dominated in the quadrats of all the other groups. Where present in quadrats of group 9, only tiny and stunted thalli of *H. physodes* occurred. The reduction in mean cover on pine trunks in the most heavily polluted quadrats is reflected in the correlation coefficients for the relation of cover to distance or copper concentration in the lichen. Though numerically low, the correlation was significant in many cases (Table 12).

4 DISCUSSION

The pollutants

All evidence accumulated suggests that the deleterious effects on the vegetation can be ascribed to the pollution with copper and zinc. These two metals made up 98% of the excess heavy-metal load of the area (Tyler 1974). The amounts of lead, cadmium and nickel emitted were presumably not large enough to contribute much to the effects. In contrast to the situation in the case of primary smelters, the amounts of SO₂ emitted from the foundries were negligible; on the contrary there was a rise in soil-surface pH due to the emission of copper and zinc in the form of oxides (Bengtsson, Nordström & Rundgren 1983, Nordgren, Bååth & Söderström 1983).

The mosses and lichens

The ground-layer vegetation showed the most evident damage from air pollution. Mosses and lichens lack roots and are to a great extent dependent on atmospheric supply for their mineral nutrition. The tissue of mosses, often only one cell layer thick and lacking a cuticle, readily absorbs and retains heavy metals (Rühling & Tyler 1970). Lichen thalli are made up of a fungus and algal cells, forming a composite structure which is susceptible to external disturbance such as air pollution. Like mosses, lichens readily accumulate heavy metals, though often to a lesser degree (Folkeson 1979, Pilegaard, Rasmussen & Gydesen 1979).

Mature forest species

The most obvious sign of the degeneration of the ground-layer vegetation near the foundries was a considerable reduction in cover of a few common species such as the feather mosses (*Pleurozium schreberi*, *Hylocomium splendens* and *Ptilium crista-castrensis*), *Dicranum polysetum*, the reindeer lichens (*Cladonia arbuscula*, *C. rangiferina* and *C. stellaris*) and *Cladonia uncialis*. These species are typical of mature ecosystems in stable environments such as coniferous forests (Tamm 1953, Ahti 1961,

1977, During 1979, Magnusson 1982, Oksanen & Ahti 1982). Along with the decrease in cover, a reduction in the biomass, length and weight has been demonstrated for annual segments of one of the feather mosses, *Hylocomium splendens*, growing in the polluted area (Bengtson, Folkeson & Göransson 1982).

The heavy-metal concentrations at which the first signs of a reduction in cover was observed were somewhat lower for the feather mosses and *Dicranum polysetum* than for the reindeer lichens and *Cladonia uncialis*. This is in contrast to the general opinion that lichens are more sensitive than mosses to air pollutants. However, the fact that a reduction in lichen cover was difficult to establish before high heavy-metal concentrations were encountered may be related to the difficulty in deciding whether a slightly discoloured and injured lichen carpet was living or not. This decision was apparently much easier to make for the feather mosses which seem to lose their green colour soon after death.

Apart from the profound effect on the cover of the common mosses and lichens, there was a pronounced reduction in species diversity, which was assessed as the number of species. Though not attaining high frequencies in the non-polluted area, many taxa were completely lacking in the most polluted area, and the number of taxa was accordingly reduced until eventually only a few taxa remained.

Pioneer species

The difference between species in sensitivity to the pollution shows some ecologically interesting features. The impression from the field is that the mosses and lichens forming large carpets or cushions (such as the feather mosses, *Dicranum polysetum*, the reindeer lichens and *Cladonia uncialis*) decrease in cover in the polluted area and give place to certain *Cladonia* *Cladonia* species. Even if the species diversity decreased towards the foundries for the lichens as well as for the mosses, a significant increase in cover from the least polluted to the moderately polluted quadrats was revealed for some *Cladonia* *Cladonia*. Among this group of lichens found at Gusum, *Cladonia*

pyxidata has been reported from a copper-zinc mine in Sweden (Nicklasson & Söderberg 1980). This species and *C. bacillaris*, *C. chlorophaea*, *C. coniocraea*, *C. deformis* and *C. floerkeana* have also been found to be toxitolerant in cities or near smelters where SO_2 is a major component of the pollution (Brodo 1966, LeBlanc 1969, Pyatt 1970, Nash 1972, 1975, Westman 1975). *Cladonia Cladonia* are typical of 'young' or disturbed habitats such as eroded sand dunes or burned forest floors (Sarvas 1937, Uggla 1958, Olsson 1974, Topham 1977, Ahti 1977, Oksanen 1981, Magnusson 1982, Oksanen & Ahti 1982). The *Cladonias* that were found to be the most tolerant to the heavy-metal pollution at Gusum are thus species that are known to be pioneers in successions. One of the *Cladonia Cladonia*, *C. uncialis*, is commonly found in early successional stages or disturbed habitats, but it often retains a high cover throughout the succession (Bayfield, Urquhart & Cooper 1981, Magnusson 1982, Oksanen & Ahti 1982). In the Gusum area it is abundant in quadrats rich in rock outcrops but it distinctly appears to be sensitive to the heavy-metal pollution. In this respect it resembles the *Cladonia Cladina* which are typical of the final stages of succession.

Some of the tolerant mosses at Gusum, *Pohlia nutans*, *Andreaea rupestris* and *Dicranum montanum*, are colonizers, too (Sarvas 1937, Olsson 1974, Westman 1975, During 1979), but their frequencies, except for *Pohlia nutans*, were low in the whole area. Also tolerant were the tiny mosses *Isopterygium elegans* and *Plagiothecium laetum*, often found under grass, and *Polytrichum commune*. The shoots of *Polytrichum* mosses show internal anatomical differentiation and emerge from an underground rhizome-like stem. These features contribute to the capability of low-growing *Polytrichum* species to rapidly colonize 'young' or disturbed habitats (Sarvas 1937, Uggla 1958, Oksanen & Ahti 1982). In addition, the complex leaf structure may play a part in the heavy-metal tolerance of *Polytrichum commune*.

Unlike some *Cladonia Cladonia*, no moss showed any positive response to the heavy-metal deposition. *Pohlia nutans*, being the sole remaining moss next to the old foundry, thrived conspicuously well in some heavily polluted places, however.

It is known as a copper-tolerant species (Dykeman & de Sousa 1966, Nicklasson & Söderberg 1980) and has been reported to cover large patches of otherwise denuded rock in the Sudbury area which is heavily polluted with mainly copper, nickel and SO_2 (Freedman & Hutchinson 1980). *Pohlia nutans* has also been shown to photosynthesize fairly satisfactorily near the Gusum foundries even with copper and zinc concentrations of 4000 and 4900 $\mu\text{g} \cdot (\text{g dry wt})^{-1}$, respectively, in its tissue (Stjernquist 1981).

Environmental factors and the chemical gradient

In the heavily polluted area, the metal pollution evidently constituted the most important factor governing the performance of the ground-layer vegetation. In unpolluted ecosystems factors such as canopy density, insolation, moisture conditions and the nature of the substrate exert an overriding influence on the mosses and lichens. But however strong the pollution factor was, it could not completely rule out these environmental factors, which decidedly had a modifying influence on the performance and species composition of the ground-layer vegetation.

When the structure of the ground-layer vegetation is to be evaluated, it is therefore appropriate to divide the set of quadrats into two classes which differ in percentage of rock outcrops and in density and composition of the tree layer, features of great importance to the ground-layer vegetation. In addition, the composition of the field-layer vegetation, reflecting the moisture and nutrient status of the soil, also influences the mosses and lichens on the ground. Groups 1, 3, 4, 6, 7 and 0 mainly comprise spruce-dominated quadrats with high canopy densities and two rock-outcrop percentages. The field-layer vegetation of the majority of the quadrats in these groups was classified into group 1 (the 'bilberry-spruce forest' type; Sjörs 1965) by the TABORD classification of the field-layer (Table 5). Groups 2, 5, 8 and 9 mainly comprise pine-dominated quadrats with low canopy densities and high rock-outcrop percentages and a dominance of group-2 quadrats ('pine wood on acid rock'; Sjörs 1965) according to the TABORD field-layer classification. A comparison of the groups in these two

classes reveals the reaction of groups of species to the combined influence from the pollutants and environmental factors.

The spruce-dominated quadrats with a low degree of pollution are abundant in feather mosses, which is typical of dark mature coniferous (group 1 in Tables 3 and 5). Signs of an influence from copper and zinc (Fig. 4) seem to be present already in group 3, where *Ptilium crista-castrensis* is almost lacking and *Dicranum polysetum* is low in cover. An increase in the occurrence of *Cladonia* *Cladonia* is observable at higher degrees of pollution. The pine-dominated quadrats with a low degree of pollution have high coverages of feather mosses (except *Ptilium crista-castrensis*) as well as of reindeer lichens (group 2). The abundance of these lichens reflects their dependence on open and dry habitats rich in rock outcrops. The scarcity of feather mosses and *Dicranum polysetum* and the abundance of reindeer lichens in group 5 indicates the higher heavy-metal sensitivity of these mosses as compared with the reindeer lichens.

The general response of the ground-layer vegetation to an increase in the deposition of copper and zinc seems to be as follows:

- 1) The disappearance of the common mosses such as the feather mosses and *Dicranum polysetum*; closely followed by
- 2) the disappearance of the common reindeer lichens (*Cladonia* *Cladina*) and *Cladonia uncialis*;
- 3) an increase in the cover of colonizers in *Cladonia* subgen. *Cladonia* and the persistence of tolerant mosses and lichens only, though the cover values are low; *Pohlia nutans* retains its cover; and, finally,
- 4) the disappearance of most of the tolerant species as well, except for *Pohlia nutans* whose cover varies independently of the heavy-metal load.

The epiphytic vegetation

The epiphytic lichen vegetation appeared to be less sensitive to heavy-metal pollution than the ground-layer vegetation. Epiphytic lichens have been considered to be more susceptible

than soil-inhabiting lichens to air pollutants (Hale 1974). Most lichen studies have been performed in areas where SO_2 is a major pollutant, however. The influence on the epiphytic lichen vegetation at Gusum would undoubtedly have been far stronger, if SO_2 had been emitted in addition to the heavy metals. The cover scale used for the assessment of the general occurrence of epiphytic vegetation was rather rough, however. On the other hand, the study devoted to lichens on pine-trunk segments was detailed. There are, however, several draw-backs to using the trunks of pine as well as of spruce as a substrate for lichens in air-pollution studies. Pines shed large flakes of bark, whereby the attached lichens are lost. Spruce trunks are often shaded by a dense canopy. The bark of both tree species is acid and supports a species-poor lichen flora. Of the epiphytes studied, only *Hypogymnia physodes* occurred in such quantities on the pine trunks that any influence from pollution could be demonstrated. The other species were too infrequent even in unpolluted areas. This finding is consistent with what was found in a Finnish study (Kauppi & Mikkonen 1980). At the same time, *H. physodes* is known as a pollution-tolerant lichen (LeBlanc 1969, Margot 1973, Westman 1975). Nevertheless at high metal levels a reduction in frequency, cover and thallial size was demonstrated. A decrease in the size of the thalli as well as morphological changes are common responses of lichens to pollution stress (Pyatt 1970, Westman 1975, Kauppi & Mikkonen 1980). *Parmeliopsis ambigua* was the species that was the next most frequent on pine stems in the present investigation. This lichen, too, is known to be toxitolérant (Topham 1977, Westman 1982).

The field layer and the trees

Deschampsia flexuosa was the only field-layer species to show any response to the pollution. It tended to increase in cover with the metal load. This common grass is known to flourish in clear-cut areas (Sjörs 1965) and has also been reported as pollution tolerant (Huttunen 1975). Reduced competition from the ground-layer species in polluted quadrats may well play a part here. Recently, however, the collapse of mats of *D. flexuosa* next to the new foundry has been observed. The

coniferous trees, known to be sensitive to SO_2 , showed no response to the heavy-metal pollution as far as density is concerned. On the hilltops next to the old foundry dead conifers had been cut down, however. Near the new foundry the trees had become blackened as a result of the deposition of oxides of copper and zinc.

The numerical methods

The statistical and numerical processing could have been greatly reduced if the aim of the study had been to merely reveal the copper-zinc gradient and its significance to single species. The use of different techniques, however, presents a more detailed picture of the great number of co-operating variables in this descriptive investigation. Thus the r_s correlations reveal the degree of relation of single species to environmental and chemical variables and between different environmental and chemical variables as well. The TABORD classification shows the discontinuity of distribution patterns of species, especially pronounced in such a polluted area. The RA ordination, although considered to present poor results with environmental data (Gauch & Wentworth 1976) produced easily interpretable results in this study. By displaying two different sets of pairs of RA axes, the generation of hypotheses concerning causal factors underlying the distribution patterns of species was facilitated. In addition, the display of TABORD classification groups on the first two RA axes linked the environmental and vegetational structures together.

The need for ordination techniques based on environmental data is urged by Orłóci (1978). The application of environmental ordination to a data set the size of this shows the advantages of this type of ordination compared with species ordination (see, for instance, corresponding results in Kvillner 1977 and Andersson & Kvillner 1983). Not only did the RA ordination of environmental and chemical data reveal the highest values of variation but it also produced results that were easily interpretable from an ecological point of view. In environmental investigations there are usually fewer missing values than in this study, but here they could usually be easily interpreted.

The design of the study

The extent of the investigation area and the great variation in the density of the net of sampling quadrats with distance were decided with regard to the very low smokestocks of both foundries. Even if the regional background concentrations of copper and zinc were not encountered, the size of the area was apparently sufficient to include the zone where the effects on the vegetation were present. The total number of quadrats investigated could have been somewhat lower, however. A 25 x 25 m quadrat was chosen so that the natural small-scale variation in the vegetation would be minimized. A strategy including many smaller subplots within larger but fewer quadrats would probably have been more optimal and less time-consuming.

It can be worth mentioning that the selection of investigation quadrats that have not been too greatly disturbed by forestry measures can be difficult even in a sparsely inhabited forested area such as the Gusum district; 152 of the proposed (1-hectare) investigation plots had to be disregarded because of clear-cutting, heavy thinning or other forestry measures. In the selected quadrats the degree of thinning had rarely any distinct influence on the vegetation, however.

The cover scale used here overestimates the lowest cover value (1) and underestimates the highest one (9). The numbers 2 and 3 were rejected in order to avoid too large an overestimation of the lowest coverage. One-letter digits were chosen for computer-technical reasons. The transformation of cover values into different scales may have some minor influence on the outcome of classification and ordination (Jensén 1978), but not on the results of correlation as long as the Spearman rank-order correlation coefficient is used.

The abundance of the ground lichen flora was strongly dependent on canopy density and the percentage of rock outcrops. Further, the classification process failed to separate other interpretable field-layer vegetation units than those typical of "pine wood on acid rock" and "bilberry-spruce forest" (Sjörs 1965). Therefore, the selection of one of the

two forest types would have been preferable, if the demonstration of pollution effects using only a sufficient number of quadrats had been the sole aim of the investigation. Clearly indicating the additional influence of environmental and biotic factors, the inclusion of both forest types, and their intermediates, has contributed to the understanding of the modifying influence that natural factors exert on the effect of air pollution on vegetation. Such interactions between natural factors and pollution stress constitute an issue that deserves to receive more attention in environmental studies (Huttunen et al. 1980, Huttunen, Havas & Laine 1981).

Prospects

Coniferous forests are by far the dominating type of forest in Fennoscandia. The effects on the forest vegetation in the surroundings of Gusum are therefore representative of much of Fennoscandia if damage to forest vegetation caused by copper and zinc emissions is to be predicted.

The ground mosses and lichens undoubtedly have a significant role in the forest ecosystem. The ground layer which they constitute regulates the climate near the ground and its destruction radically alters conditions for the life and function of the soil organisms. This forms an additional stress factor for the soil biota living in a metal-polluted environment. Moreover, the nitrogen-fixing algae of many lichens contribute mineral nitrogen to these nutrient-poor forests.

Mosses and lichens are the most important colonizers of bare rocks, building up a humus layer where higher plants can root. When the mosses and lichens are destroyed, the thin soil becomes prone to erosion. Cliffs denuded in this way are common in the vicinity of the old foundry and denudation is proceeding near the new foundry as well. In spite of the ability of *Pohlia nutans* to grow in the heavily polluted environment, colonization of the denuded rocks by this and other species, after the planned reduction of emissions, will undoubtedly be a very slow process. And where the soil is deeper, the strong retention of zinc and especially copper

by the organic matter of the soil will prevent the establishment of a normal carpet of mosses and lichens until far into the future.

5 CONCLUSIONS

- * In the coniferous forest surrounding the two brass foundries the copper concentration of raw humus was found to increase from 22-25 $\mu\text{g}(\text{g organic dry wt})^{-1}$ at a distance of 7 km to well above 8000 $\mu\text{g}\cdot\text{g}^{-1}$ close to the new foundry. The corresponding zinc gradient was less steep, rising from 80-100 to well over 6000 $\mu\text{g}\cdot\text{g}^{-1}$. The regional background concentrations of copper and zinc were not found within the area.
- * The Common mosses together cover 20-40% (in some cases more than 75%) of the forest floor at remote sites. The moss cover began to diminish where the copper and zinc concentrations in the moss tissue reached values 3-5 times (Cu) and twice (Zn) the values found at the remote sites. At concentrations of c. 100 $\mu\text{g}\cdot\text{g}^{-1}$ for copper and c. 300 $\mu\text{g}\cdot\text{g}^{-1}$ for zinc, the cover was reduced to virtually zero. Except for a few scattered occurrences *Pleurozium schreberi*, *Hylocomium splendens*, *Ptilium crista-castrensis*, *Dicranum polysetum*, *D. scoparium* and *Aulacomnium palustre* were not found within 1 km of the foundries. Dead and blackened moss tissue was frequently encountered near the new foundry, however. The cover of the reindeer lichens (*Cladonia* subgen. *Cladina*) and *C. uncialis* suffered a similar reduction, starting at higher metal levels.
- * The species diversity of the ground-layer vegetation declined considerably. The mean number of moss taxa found in the 25 x 25 m quadrats fell from 15-18 in remote quadrats to 3-4 near the foundries. The number of *Cladonia* taxa declined correspondingly from 10-12 in remote quadrats with a high rock-outcrop percentage to about 2 near the foundries. *Cladonia* lichens appeared to be less sensitive than mosses to heavy metals and were obviously dependent

on the presence of suitable substrates, preferably bare rock.

- * The general response of the ground-layer vegetation to the increase in the deposition of copper and zinc was as follows:
 - 1) The disappearance of the common mosses such as the feather mosses and *Dicranum polysetum*, typical of mature forests; closely followed by
 - 2) the disappearance of the common reindeer lichens (*Cladonia Cladina*) and *Cladonia uncialis*, typical of dry and thin mature forests where rock outcrops are abundant;
 - 3) an increase in the cover of colonizers in *Cladonia* subgen. *Cladonia* and the persistence of tolerant mosses and lichens only, though the cover values were low; *Pohlia nutans* retained its cover; and, finally
 - 4) the disappearance of most of the tolerant species as well, except for *Pohlia nutans* whose cover varied independently of the heavy-metal load.

- * The copper and zinc pollution was the most important factor regulating cover and species diversity of the mosses and lichens. It could not, however, completely mask the influence of environmental factors such as canopy density, rock-outcrop percentage, dryness of the soil surface and degree of exposure of the stand. Environmental ordination (Reciprocal Averaging) proved to be superior to species ordination in revealing the influence of these environmental factors.

- * The occurrence of lichens on trunks and twigs of spruce and pine decreased with increase in metal load. The frequency and cover of *Hypogymnia physodes* and the thallus size were reduced at heavily polluted sites.

- * No influence of pollution was registered for the cover of field-layer species apart from a tendency for *Deschampsia flexuosa* to increase in cover with the concentration of heavy metals in raw humus.

- * Soil biota will suffer from the deterioration of the ground layer that regulates the climate near the ground. The thin soil is prone to erosion. Recolonization will be much delayed by the high metal concentrations in the top soil and by the absence of soil on the denuded rock outcrops.

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Table 1. Number of quadrats in zones and sectors of the investigation area surrounding the two foundries at Gusum. See further Fig. 1.

Zone	Distance from the nearest foundry	Number of quadrats in each sector							
		E	N	W	S				
1	0-1 km	12	+	12	+	12	+	12	= 48
2	1-2 km	11	+	11	+	11	+	11	= 44
3	2-3 km	7	+	7	+	7	+	7	= 28
4	3-4 km	5	+	5	+	5	+	5	= 20
5	4-5 km	4	+	4	+	4	+	4	= 16
6	5-6 km	3	+	3	+	3	+	3	= 12
7	6-7 km	3	+	3	+	3	+	3	= 12

Table 2. Spearman correlation coefficients r_s for the relationships between the distance of the quadrat from the new foundry and some metal concentrations in raw humus under Cladonia rangiferina, in the lichen tissue and in epiphytic Hypogymnia physodes sampled from pine trunks.

Raw humus under Cladonia rangiferina			Cladonia rangiferina			Hypogymnia physodes		
	r_s	n		r_s	n		r_s	n
Cu	-0.91***	157	Cu	-0.95***	125		-0.93***	161
Zn	-0.89***	156	Zn	-0.93***	125		-0.89***	161
Cu+Zn	-0.90***	156	Pb	-0.75***	124		-0.46***	160
Ca	-0.09	119	Ni	-0.44***	113		0.24***	161
			Cd	0.22**	112		0.22**	160
			Fe	-0.81***	113		0.08	143
			Mn	-0.53***	125		-0.04	159
			Mg	-0.69***	125		0.02	117
			Ca	-0.60***	125		0.25***	161
			K	-0.15*	125		-0.75***	117
			Na	-0.27**	113		0.36***	117

*** $p < 0.001$

** $p < 0.01$

* $p < 0.05$.

Table 3. TABORD classification of 82 ground-layer species (57 Musci and 25 Cladonia taxa) on 180 quadrats in the area surrounding the brass foundries at Gusum. Threshold value 0.40 and fusion limit 0.80 gave nine clusters (1-9) and a residual group (0). Only taxa with frequencies $\geq 25\%$ in any cluster included in the table.

[illegible]

Quadrats of groups 1, 3, 4, 6, 7 and 0 are dominated by *Picea abies*, quadrats of groups 2, 5, 8 and 9 are dominated by *Pinus sylvestris*.
Quadrats belonging to groups with low numbers are far from the foundries and quadrats with higher numbers (0 included) are closer to the foundries.
* includes *Cladonia chlorophaea*, *C. grayi*, *C. cryptochlorophaea*, *C. merochlorophaea* and *C. pyxidata*.

Table 4. Metal concentrations, $\mu\text{g}(\text{g dry wt})^{-1}$, in *Cladonia rangiferina* sampled from quadrats belonging to different groups in the TABORD classification of the ground-layer vegetation.

Group	Cu	Zn	Pb	Ni	Fe	Mn	Ca
1	12 $\pm$	96 $\pm$ 29 (16)	21 $\pm$	1.5 $\pm$ 0.4 (16)	386 $\pm$	54 $\pm$ 25 (16)	362 $\pm$ 85 (16)
2	22 $\pm$	118 $\pm$ 56 (53)	25 $\pm$	1.6 $\pm$ 0.4 (53)	505 $\pm$	41 $\pm$ 21 (53)	324 $\pm$ 71 (53)
3	33 $\pm$	192 $\pm$ 80 (6)	34 $\pm$	1.9 $\pm$ 0.2 (4)	428 $\pm$	70 $\pm$ 19 (7)	530 $\pm$ 120 (7)
4	86 $\pm$	321 $\pm$ 103 (22)	41 $\pm$	1.9 $\pm$ 0.3 (17)	793 $\pm$	69 $\pm$ 26 (22)	494 $\pm$ 128 (22)
5	129 $\pm$	385 $\pm$ 165 (14)	38 $\pm$	1.8 $\pm$ 0.6 (12)	854 $\pm$	51 $\pm$ 20 (14)	383 $\pm$ 75 (14)
6+7+8	399 $\pm$	556 $\pm$ 198 (6)	65 $\pm$	3.1 $\pm$ 0.5 (5)	1210 $\pm$	66 $\pm$ 30 (6)	486 $\pm$ 119 (6)
9+0	1400 $\pm$ 1290 (9)	1140 $\pm$ 912 (9)	179 $\pm$ 195 (9)	4.8 $\pm$ 1.1 (8)	1870 $\pm$	117 $\pm$ 41 (9)	674 $\pm$ 159 (9)

Arithmetic mean $\pm$ s.d.(n). Some groups combined to increase n.

Table 5. Characteristics of the ten quadrat groups in the TABORD classification of the ground-layer vegetation in the area surrounding the foundries at Gusum.

TABORD group	n	No. of spruce-dominated quadrats 1)	No. of pine-dominated quadrats 2)	No. of spruce trees per quadrat	No. of pine trees per quadrat	Canopy density (%)	Rock outcrop percentage	No. of moss taxa per quadrat	No. of Cladonia taxa per quadrat	No. of field-layer taxa per quadrat
1	21	18	3	33.5±13.9	14.1±12.7	59±21	5.4±11	15.9±4.1	7.0±3.8	26.8± 9.9
2	64	26	38	13.2±13.9	18.5± 9.0	27±16	45 ±32	17.9±3.6	12.2±2.1	18.1± 8.0
3	9	9	0	25.2± 8.0	7.9± 6.1	59±16	0.2± 0.7	13.4±3.3	5.9±1.5	33.9± 4.9
4	25	20	5	17.0±13.1	10.8± 7.7	30±19	28 ±31	12.4±4.2	11.3±2.2	25.0± 8.4
5	16	3	13	9.6±12.2	15.4± 6.8	26±14	56 ±41	8.4±3.2	10.6±2.5	15.9± 6.5
6	6	6	0	17.5± 8.4	10.2± 5.4	43±27	15 ±18	5.8±3.8	6.7±2.3	24.7± 7.6
7	5	3	2	18.4±15.0	8.0± 6.0	35±16	17 ±35	6.2±2.4	4.0±1.7	19.4± 4.2
8	8	4	4	8.4±12.2	10.9± 4.3	26±16	64 ±21	6.1±2.9	6.4±2.1	18.5± 6.6
9	7	3	3*	5.1± 5.8	8.4± 4.2	15±11	58 ±29	2.6±1.4	1.9±1.9	14.7± 9.0
0	19	14	5	14.1±10.1	9.9± 6.8	26±13	23 ±29	3.5±2.2	2.3±2.7	23.2±11

Arithmetic mean ± s.d.

1) Group 1 in the TABORD classification of the field-layer vegetation (Bilberry-spruce forest; Sjörs 1965)

2) Group 2 in the TABORD classification of the field-layer vegetation (Pinewood on acid rock; Sjörs 1965)

* Plus one quadrat (field-layer species absent) constituting the residual group in the TABORD classification of the field-layer vegetation.

Table 6. Spearman correlation coefficients r_s for the relationships between chemical and environmental variables, and the cover of some moss taxa (and the number of taxa) in quadrats 0-7 km (first three columns) or 2-7 km (last three columns) from the nearest foundry.

	Distance from new foundry (n=180)	Cu in raw humus (n=157)	Cu+Zn in the respective species (n=88)	Rock outcrop percentage (2-7 km) (n=88)	Canopy density (2-7 km) (n=88)	Topography (2-7 km) (n=88)
<i>Andreaea rupestris</i>	0.32***	-0.29***		0.49***	-0.35***	0.35***
<i>Aulacomnium androgynum</i>	0.24***	-0.23**		0.03	-0.15	0.14
<i>A. palustre</i>	0.67***	-0.69***		0.04	-0.10	0.00
<i>Dicranum polysetum</i>	0.84***	-0.87***	-0.63*** (n=88)	-0.09	0.19*	-0.03
<i>D. scoparium</i>	0.70***	-0.71***		-0.29**	0.32***	0.04
<i>Hylacomium splendens</i>	0.78***	-0.78***	-0.28** (n=74)	-0.34***	0.35***	0.00
<i>Hypnum cupressiforme</i>	0.51***	-0.45***	0.18 (n=64)	-0.10	0.25**	0.29**
<i>Isopterygium elegans</i>	-0.09	0.03		0.05	0.00	0.34***
<i>Plagiomnium affine</i>	0.26***	-0.19**		-0.54***	0.41***	-0.17
<i>Plagiothecium laetum</i>	0.12*	0.02		-0.03	0.10	0.32***
<i>Pleurozium schreberi</i>	0.88***	-0.89***	-0.57*** (n=102)	-0.35***	0.34***	-0.10
<i>Pohlia nutans</i>	0.11	0.03		0.36***	-0.26**	0.26**
<i>Polytrichum commune</i>	0.09	0.08		0.59***	-0.51***	-0.07
<i>Ptilium crista-castrensis</i>	0.51***	-0.57***		-0.40***	0.35***	0.02
<i>Racomitrium heterostichum</i>	0.41***	-0.40***		0.52***	-0.41***	0.26**
<i>Rhytidiadelphus triquetrus</i>	0.35***	-0.35***		-0.38***	0.35***	-0.11
Number of moss taxa	0.70***	-0.68***		0.07	-0.01	0.35***

Topography = height difference within the 25x25 m quadrat. See Fig. 5 for cover scale.

Table 7. Spearman correlation coefficients r_s for the relationships between chemical and environmental variables, and the cover of some *Cladonia* taxa (and the number of taxa) in quadrats in the area surrounding the brass foundries at Gusum.

	Distance from new foundry (n=180)	Cu in raw humus (whole gradient) (n=157)	Cu in raw humus (less than 700 ppm) (n=139)	Rock outcrop percentage (2-7 km) (n=88)	Canopy density (2-7 km) (n=88)	Topography (2-7 km) (n=88)
<i>Cladonia arbuscula</i>	0.50***	-0.35***				
<i>C. bacillaris et floerkeana</i>	0.06	0.03		0.84***	-0.67***	0.11
<i>C. chlorophaea</i> agg.	-0.02	0.20**	0.50***	0.25*	-0.19*	0.05
<i>C. coniocraea et</i> <i>ochrochlora</i>	0.06	0.05	0.20**	0.41***	-0.30**	0.24*
				-0.15	0.19*	0.17
<i>C. cornuta</i>	-0.01	0.15*	0.36***	0.35***	-0.22*	0.19*
<i>C. fimbriata</i>	-0.19**	0.34***	0.52***	-0.05	0.01	0.04
<i>C. furcata</i>	0.05	0.10	0.35***	-0.02	0.23*	0.00
<i>C. gracilis</i>	0.17**	-0.04	0.18*	0.56***	-0.47***	0.22*
<i>C. rangiferina</i>	0.54***	-0.40***		0.81***	-0.63***	0.14
<i>C. stellaris</i>	0.42***	-0.36***		0.65***	-0.46***	0.08
<i>C. uncialis</i>	0.47***	-0.41***		0.79***	-0.66***	0.19*
Number of <i>Cladonia</i> taxa	0.44***	-0.24***	0.03	0.58***	-0.46***	0.29**

First two columns: the whole gradient. Third column: only quadrats where the Cu concentration in raw humus under *C. rangiferina* was below 700 $\mu\text{g} \cdot (\text{g dry wt})^{-1}$. Last three columns: quadrats 2-7 km from the nearest foundry. Topography = height difference within the 25x25 m quadrat.
 *** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$.

Table 8. Spearman correlation coefficients r_s for the relationships between distance from the foundries and environmental variables in 25x25 m quadrats in the area surrounding the brass foundries at Gusum.

	Distance from new foundry (n=180)	Distance from old foundry (n=180)
Rock-outcrop percentage	-0.08	-0.07
Topography	-0.25***	-0.22**
Canopy density	0.20**	0.17**
Number of spruce trees	0.17*	0.15*
Degree of thinning	-0.05	-0.15*
Exposure	-0.14*	-0.14*
Dryness of soil surface	-0.15*	-0.14*

Topography = height difference within the quadrat.

Degree of thinning, degree of exposure and dryness of soil surface assessed on four-point scales.

*** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$.

Table 9. Sensitivity of mosses, lichens and epiphytic vegetation to heavy metals in the area surrounding the Gusum foundries, emitting Cu and Zn but essentially no SO₂.

	No of samples analysed for metals	Metal	Concentration in remote quadrats (6-7 km)	First signs of reduction in cover	Obvious reduction in cover	Apparent threshold conc. for survival $\mu\text{g.g}^{-1}$
Pleurozium schreberi	102	Cu:	10- 15	30	40	70
		Zn:	85-100	170	200	300
Hylocomium splendens	74	Cu:	14- 18	50	80	110
		Zn:	90-100	190	240	320
Dicranum polysetum	88	Cu:	11- 16	25	35	80
		Zn:	100-120	150	190	330
Hypnum cupressiforme	64	Cu:	11- 16	60	90	100
		Zn:	95-120	290	350	400
Pohlia nutans	73	Cu:	12- 16	None	None	Not found
		Zn:	100-130			
Cladonia rangiferina	130	Cu:	5- 7			250
		Zn:	55- 75			600
Hypogymnia physodes	160	Cu:	11- 15	300	600	700
		Zn:	95-140	1300	1800	1900
Epiph. vegetation on pine trunks		Cu:	See	120	180	1000
		Zn:		640	840	2200
Epiph. vegetation on spruce trunks		Cu:	Hypo-	80	100	1000
		Zn:		480	580	2200
Epiph. vegetation on pine twigs		Cu:	gymnia	130	160	1000
		Zn:		680	840	2200
Epiph. vegetation on spruce twigs		Cu:	physodes	80	120	1000
		Zn:		480	640	2200

Dependent variables: the cover of the respective moss species and of Cladonia rangiferina; the cover of Hypogymnia physodes in segments (breadth 20 cm) of Pinus sylvestris trunks; the general occurrence of epiphytic lichen vegetation (as a whole) on four substrates as estimated on a simple four-point scale. Concentrations, $\mu\text{g (g dry wt)}^{-1}$, in the respective species (H. physodes here represents all epiphytes). The last column mostly refers to concentrations in apparently moribund plants. Concentrations in remote quadrats were slightly higher than the regional background. The concentration limits were originally judged from copper concentrations. The values are to be seen as rough approximations.

Table 10. Spearman correlation coefficients r_s for the relationships between chemical and environmental variables, and the occurrence of epiphytic lichen vegetation on trees in quadrats at 0-7 km (first three columns) or 2-7 km (last four columns) from the nearest foundry.

	Distance from new foundry	Cu conc. in raw humus 1)	Cu+Zn in Hypogymnia physodes 2)	Rock outcrop percentage (2-7 km)	Canopy density (2-7 km)	Thinning 3) (2-7 km)	Topography 4) (2-7 km)
On pine trunks	0.43*** (179)	-0.35*** (157)	-0.45*** (160)	0.44*** (87)	-0.24* (87)	-0.16 (87)	0.17 (87)
On spruce trunks	0.45*** (166)	-0.33*** (145)	-0.47*** (149)	0.11 (81)	-0.07 (81)	-0.07 (81)	0.27** (81)
On pine twigs	0.57*** (178)	-0.43*** (156)	-0.62*** (159)	0.20* (87)	0.08 (87)	-0.15 (87)	0.14 (87)
On spruce twigs	0.63*** (166)	-0.57*** (145)	-0.69*** (149)	0.31** (81)	-0.07 (81)	-0.08 (81)	-0.03 (81)

Epiphytic vegetation estimated using the scale: 3 = abundant, 2 = ordinary (normal), 1 = sparse, 0 = lacking or nearly so.

- 1) Raw humus under *Cladonia rangiferina*.
 - 2) Hypogymnia physodes on pine trunks.
 - 3) Degree of thinning as estimated on a simple four-point scale.
 - 4) Height difference within the 25x25 m quadrat.
- *** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$. Number of quadrats in parentheses.

Table 11. Frequency of lichens in quarters of segments (breadth 20 cm; at breast-height) of pine trunks in the quadrats belonging to the ten groups of the TABORD classification of the ground-layer vegetation in the area surrounding the foundries at Gusum.

	Group									
	1	2	3	4	5	6	7	8	9	0
No. of quadrats (n)	21	64	9	25	16	6	5	8	7	19
No. of segment quarters	252	768	108	300	192	72	60	96	84	228
<i>Hypogymnia physodes</i>	98 ¹⁷	97 ¹⁷	98 ²⁹	95 ¹⁹	93 ¹⁵	97 ¹⁸	97 ¹²	96 ¹¹	65 ⁷	95 ¹¹
<i>Parmeliopsis ambigua</i>	40	58	34	56	67	53	53	75	40	64
<i>P. aleurites</i>	12	44	5	23	47	22	13	27	5	17
<i>Hypocenomyce scalaris</i>	6	10	2	13	28	14	7	20	7	10
<i>Bryoria</i> spp.	15	30	13	31	21	8	4	15	1	15
<i>Usnea</i> spp.	7	24	4	21	21	6	3	10	1	4
<i>Pseudevernia furfuracea</i>	8	22	4	10	20	7	3	28	5	7
<i>Platismatia glauca</i>	6	9	3	4	5	-	3	4	-	5
<i>Cladonia</i> sect. <i>Cenomyce</i>	6	3	5	4	2	-	2	1	-	1
<i>Cetraria chlorophylla</i>	2	4	<1	5	4	-	-	2	2	<1
<i>C. pinastri</i>	<1	<1	<1	2	-	-	-	5	2	<1
<i>Hypogymnia bitteriana</i>	-	-	-	<1	-	-	-	-	-	-

Frequency = percentage of quarters (n quadrats x 3 trees x 4 compass quarters) containing the species. For *H. physodes* the characteristic degree of cover (C) is given as an exponent; C = mean cover percentage in those quarters that contain the species. In many quarters *P. glauca* and *P. furfuracea* covered up to 5%, but the other taxa seldom exceeded a cover of 2%.

Table 12. Spearman correlation coefficients r_s for the relationship between the distance of the quadrat from the foundries and the Cu concentration in Hypogymnia physodes (sampled from Pinus sylvestris trunks), and the mean cover percentage of the same lichen in N, W, S and E quarters of segments (breadth 20 cm) of pine trunks.

	Distance from new foundry (n=180)	Distance from old foundry (n=180)	Cu conc. in Hypogymnia physodes (n=161)
N quarters	0.16*	0.13*	-0.14*
W quarters	0.23***	0.12	-0.19**
S quarters	0.20**	0.12	-0.18*
E quarters	0.25***	0.21**	-0.28***

The cover values were taken as the arithmetic mean of three trees in each quadrat; n = number of quadrats.

*** $p < 0.001$ ** $p < 0.01$ * $p < 0.05$.

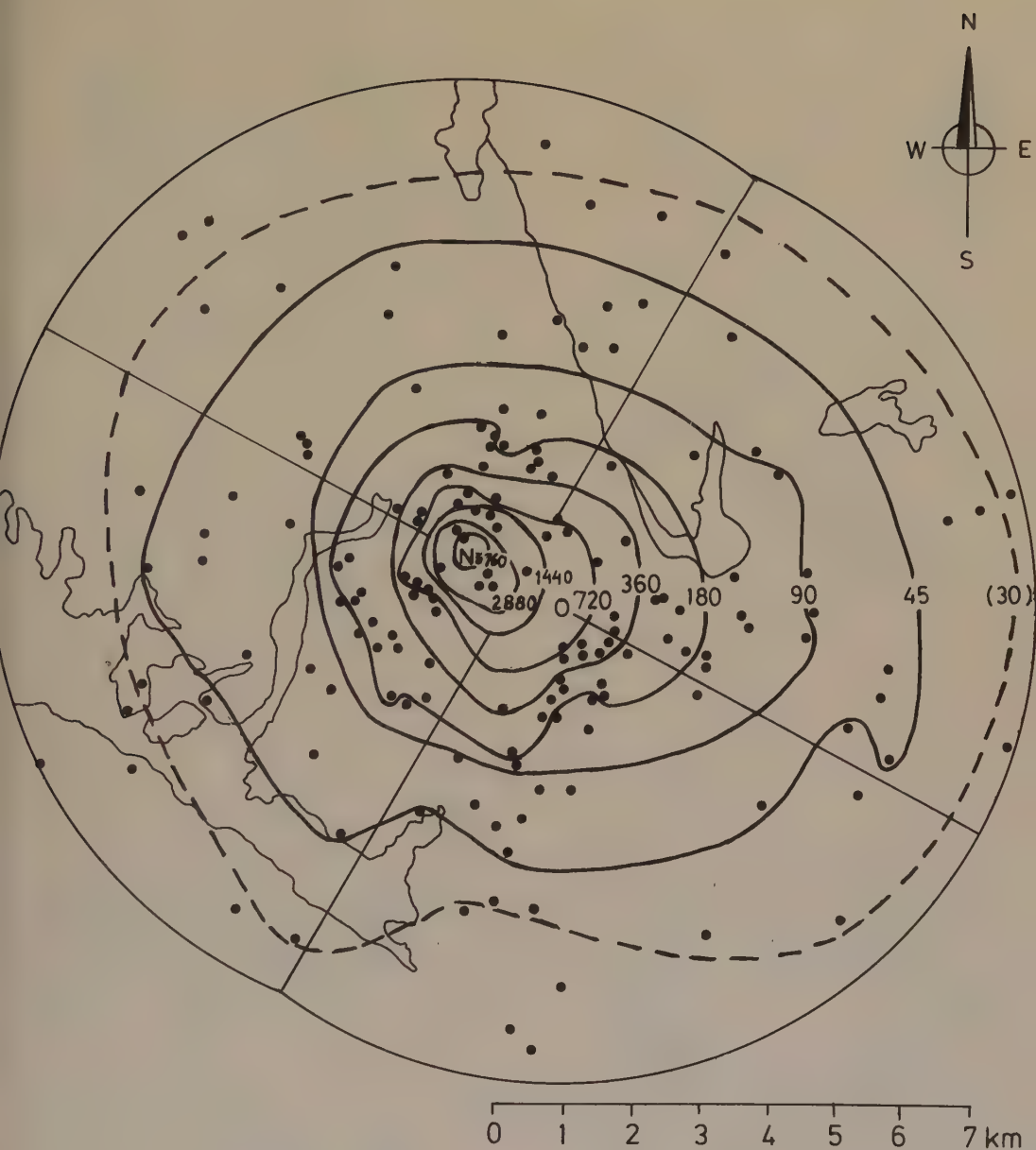
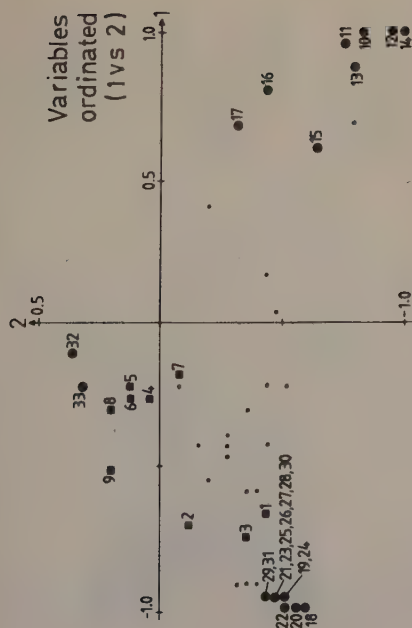


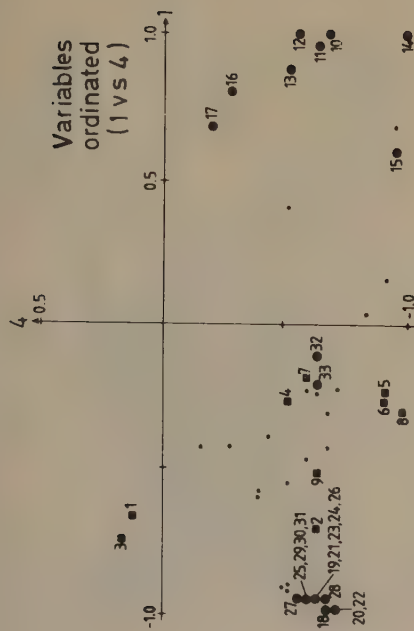
Fig. 1. Copper concentrations, $\mu\text{g}(\text{g organic dry wt})^{-1}$, in raw humus (0–2 cm; under *Cladonia rangiferina*) from 157 quadrats (indicated by dots) in the area surrounding the old (O) disused brass foundry in the centre of Gusum (1600 inhabitants) and the new (N) foundry which has been in use since 1968. Copper and zinc were closely correlated: $y = 0.75x + 0.85$ where x and y are $\lg \text{Cu}$ and $\lg \text{Zn}$ values, respectively; $r_s = 0.98$ ($p < 0.001$).

Fig. 2. RA ordination of 52 environmental and chemical variables (listed below) on 179 quadrats in the area surrounding the brass foundries at Gusum. The four axes account for 0.58, 0.27, 0.22 and 0.19 of the variation in terms of estimated eigenvalues and are scaled in proportion to the eigenvalues. a-b: Displays of variable ordination. c-1: Displays of quadrat ordination on axes 1 and 2.

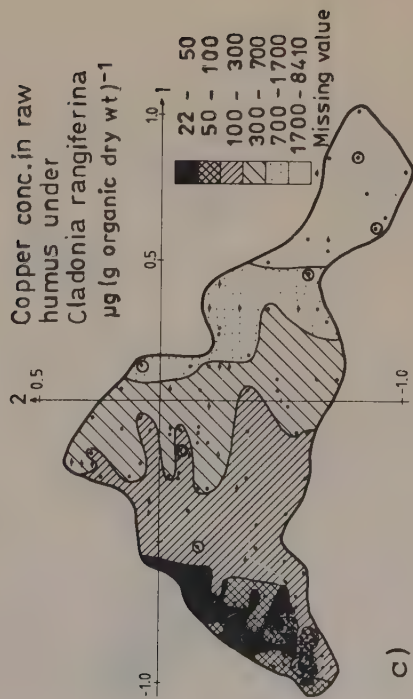
a) Axis 1 versus axis 2	d) Classification groups in the	h) Cover of <i>Pohlia nutans</i>
b) Axis 1 versus axis 4	TABORD classification of the	i) Cover of <i>Cladonia rangiferina</i>
■ Environmental variables 1-9	ground-layer vegetation	j) Rock-outcrop percentage
● Chemical variables: Cu or Zn 10-33	e) Cover of <i>Pleurozium schreberi</i>	k) Cover of <i>Cladonia chlorophaea</i> agg.
* Chemical variables: other metals 34-52	f) Cover of <i>Ptilium crista-</i>	l) General occurrence of epiphytic
c) Copper concentration in raw humus	castrensis	lichen vegetation on spruce twigs
under <i>Cladonia rangiferina</i>	g) Cover of <i>Dicranum polysetum</i>	
ENVIRONMENTAL VARIABLES:		
(1-9)	CHEMICAL VARIABLES:	
1 no. of spruce trees (n=179)	Copper and zinc (10-33)	
2 no. of pine trees (n=179)	10 Cu (n=157) and 11 Zn (n=156) in raw humus	34 Ca in raw humus under
3 canopy density (n=179)	(0-2 cm) under <i>Cladonia rangiferina</i>	<i>C. rangiferina</i> (n=125)
4 degree of thinning	12 Cu (n=129) and 13 Zn (n=131) in raw humus	35 Ditto under <i>H. splend-</i>
(n=179)	(0-2 cm) under <i>Hylacomium splendens</i>	<i>ens</i> (n=130)
5 degree of exposure (n=179)	14 Cu and 15 Zn in <i>C. rangiferina</i> (n=125)	36 Pb and 37 Ca in green
6 dryness of soil surface	16 Cu and 17 Zn in <i>Hypogymnia physodes</i> (n=161)	portion of <i>P. schre-</i>
(n=179)	18 Cu and 19 Zn in <i>Pohlia nutans</i> (n=73)	<i>beri</i> (n=101)
7 topography = height dif-	20 Cu and 21 Zn in <i>H. splendens</i> (n=74)	38 Ca in <i>D. polysetum</i>
ference within quadrat	22 Cu and 23 Zn in <i>Usnea cf. filipendula</i> (n=72)	(n=87)
(n=179)	24 Cu and 25 Zn in brown portion of <i>Pleurozium</i>	39-45 Pb, Ni, Cd, Fe, Mn,
8 rock-outcrop	<i>schreberi</i> (n=91)	Mg and Ca in <i>C. rangi-</i>
percentage (n=179)	26 Cu and 27 Zn in ditto green (n=102)	<i>ferina</i> (n=112-125)
9 area of steeply sloping	28 Cu and 29 Zn in <i>Dicranum polysetum</i> (n=88)	46-52 Pb, Ni, Cd, Fe, Mn,
bare rock (n=97)	30 Cu and 31 Zn in <i>Hypnum cupressiforme</i> (n=64)	Mg and Ca in <i>H. physo-</i>
	32 Cu and 33 Zn in <i>Pseudevernia furfur.</i> (n=123)	<i>des</i> (n=117-161)



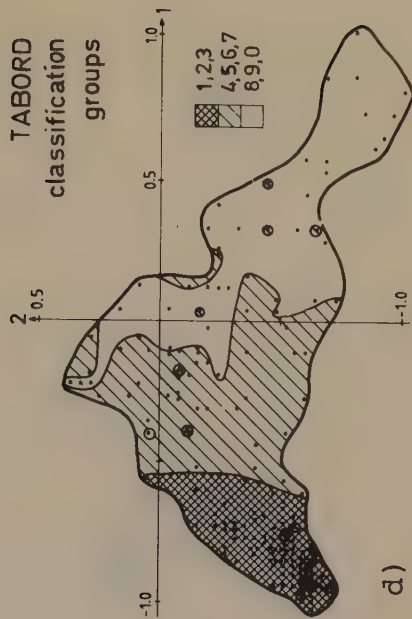
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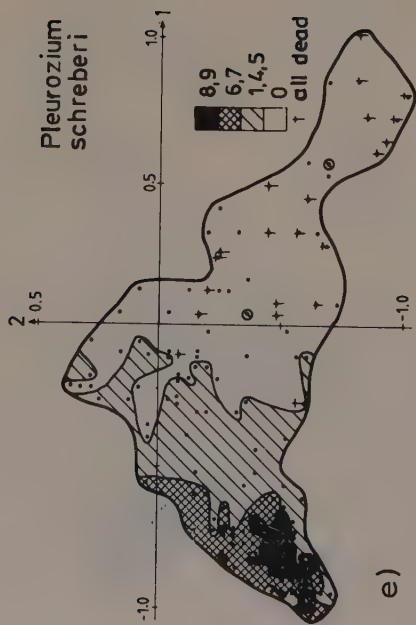
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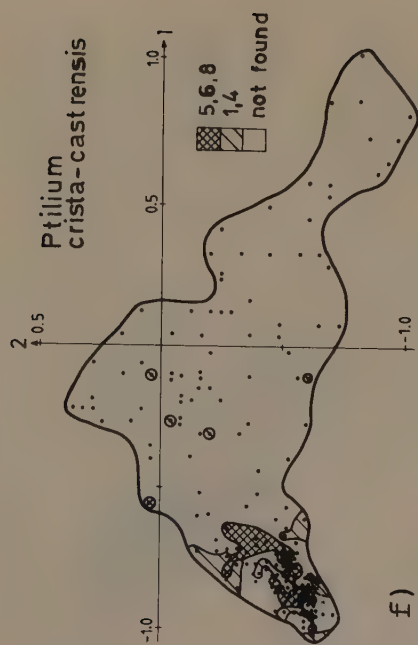
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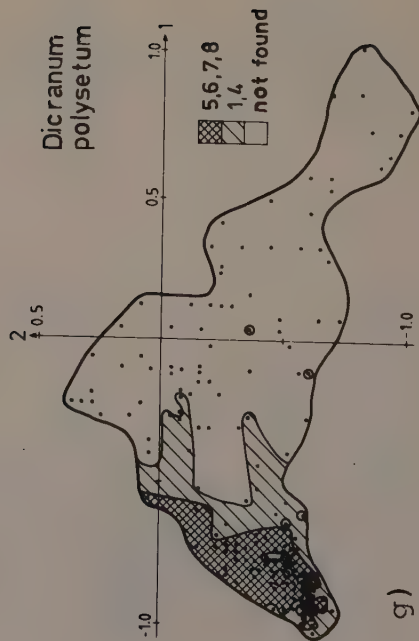
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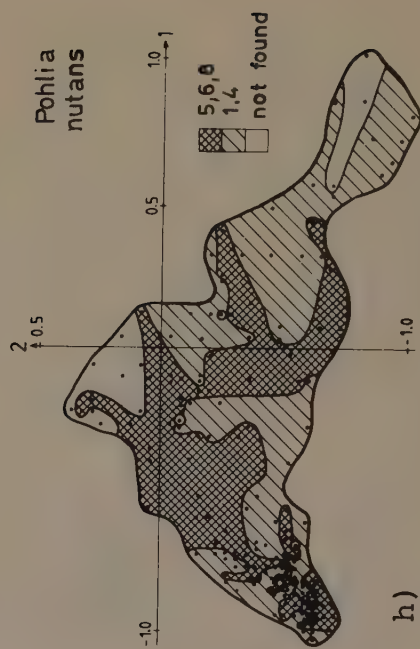
e)



f)



g)



h)

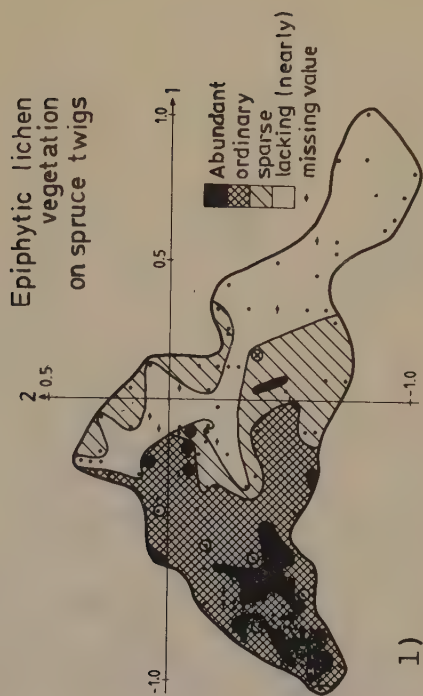
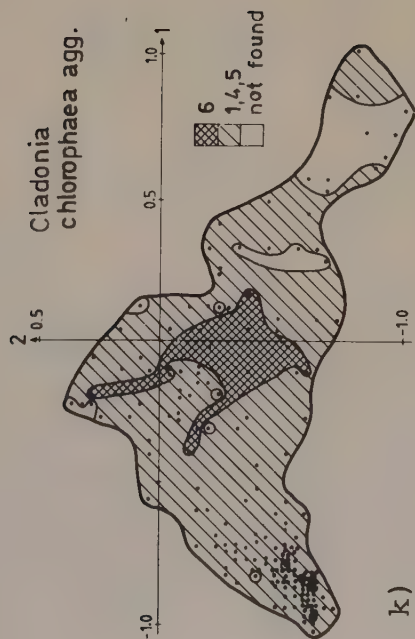
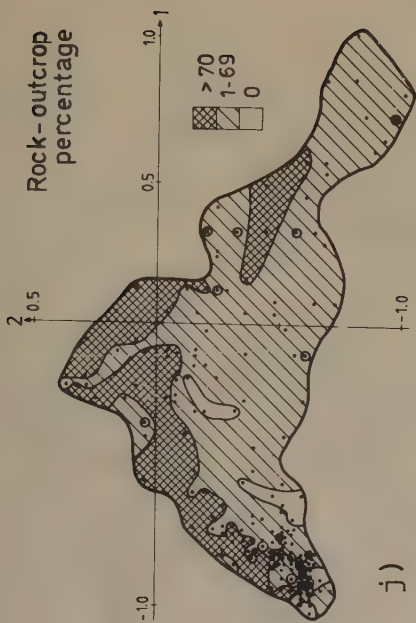
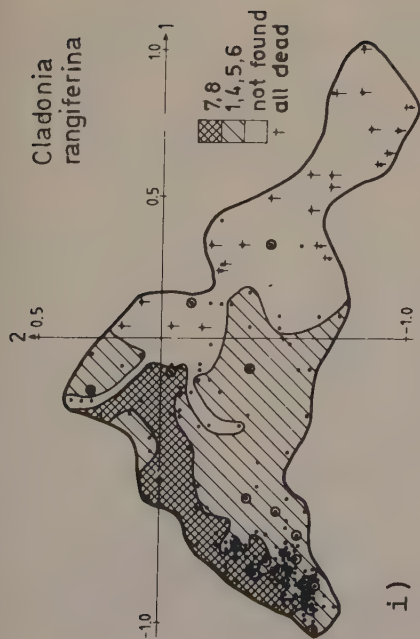




Fig. 3. Distribution of quadrats belonging to the ten groups in the TABORD classification of the ground-layer vegetation in the coniferous forest surrounding the old (O) and new (N) foundry.

Fig. 3a: 2-7 km, Fig. 3b: 0-2 km.

TABORD
classi-
fication
groups:

- | | |
|-----|-----|
| ● 1 | ⊘ 6 |
| ◐ 2 | ⊙ 7 |
| ◑ 3 | ⊗ 8 |
| ◒ 4 | ⊕ 9 |
| ⊕ 5 | ○ 0 |

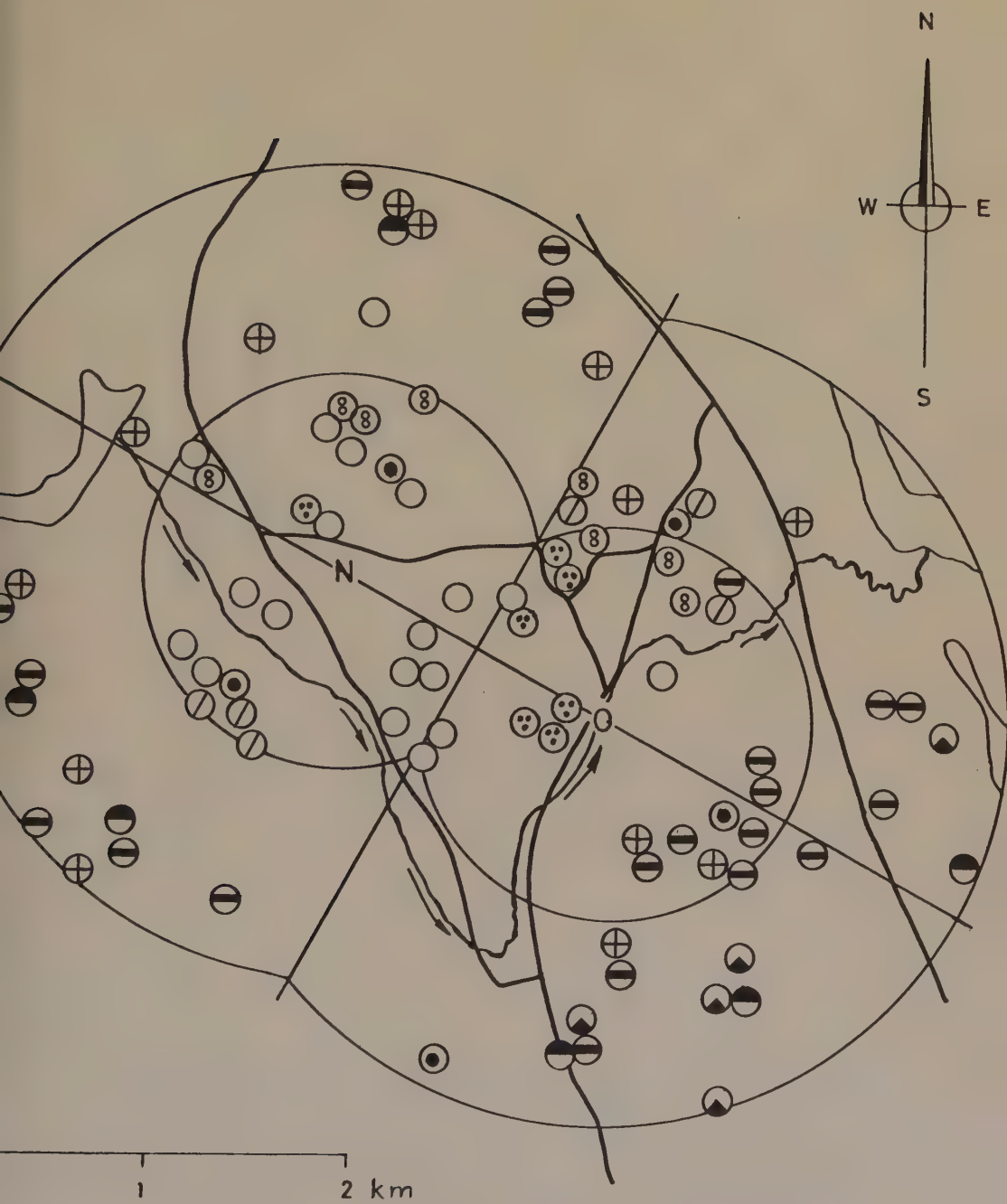


Fig. 3b.

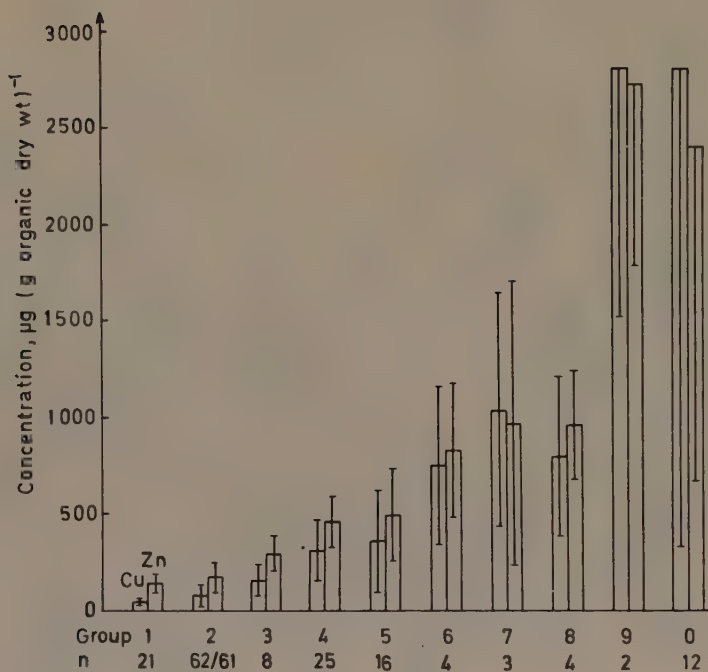


Fig. 4. Copper (left bar) and zinc (right bar) concentrations in raw humus (0–2 cm) under *Cladonia rangiferina* in quadrats belonging to the ten groups in the TABORD classification of the ground-layer vegetation in the area surrounding the brass foundries at Gusum, SE Sweden. Arithmetic mean $\pm$ s.d. n = number of samples.

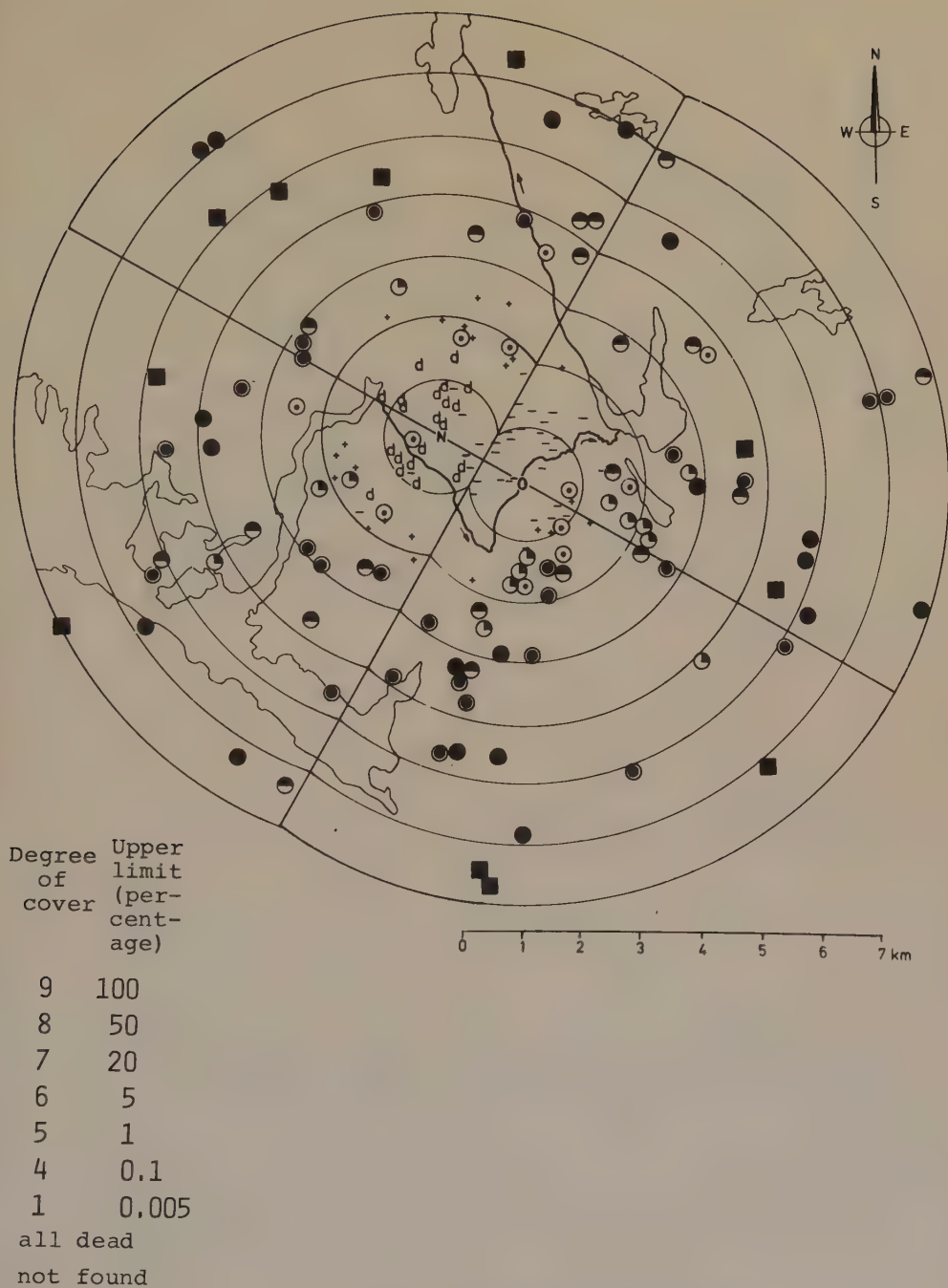


Fig. 5. Degree of cover of *Pleurozium schreberi* in 25 x 25 m quadrats in the coniferous forest surrounding the old (O) disused brass foundry and the new (N) brass foundry at Gusum (1600 inhabitants), SE Sweden.

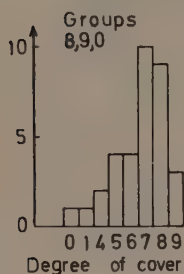
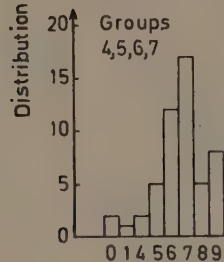
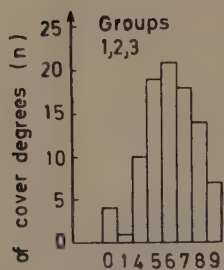


Fig. 6. *Deschampsia flexuosa*: degree of cover in quadrats belonging to groups 1-3 (n=94), 4-7 (n=52) and 8+9+0 (n=34) in the TABORD classification of the ground-layer (mosses and lichens) vegetation in the coniferous forest surrounding the brass foundries at Gusum. See Fig. 5 for cover scale.

Next page: —————>

Fig. 7. *Hypogymnia physodes*: distribution of thallial size scores (left-hand scale) and mean cover (right-hand scale) in N, W, S and E quarters of segments (breadth 20 cm) of *n* *Pinus sylvestris* trunks (three trees per quadrat) belonging to the ten groups in the TABORD classification of the ground-layer vegetation in the area surrounding the foundries at Gusum. Size scores: L = large and well-developed thalli; O = ordinary (normal) in size and appearance; T = tiny and stunted; - = *Hypogymnia physodes* absent.

Mean cover = sum of cover percentages in the *n* quarters divided by *n*. Arithmetic mean (one s.d. indicated downwards) within each of the N, W, S and E quarter of the segment.

